HYDRO-ELECTRIC ENGINEERING

Volume II

ELECTRICAL

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ELECTRIC

CHAPTER I

Water-wheel Generators

Types; frequency and number of phases; voltage.

1. Types.—Generators to be driven by hydraulic turbines include a variety of constructional forms, ranging from the simple open- or engine-type machine, which is often applicable to the smallest units, to constructions approaching that of steam-turbine driven alternators, which are necessary for the largest high-speed machines. The general difficulties in the design of the larger sets may be divided into electrical and mechanical. The electrical difficulties arise from the extremely large outputs commonly required in a single unit, running at the high speed characteristic of the water turbine. At normal frequencies this represents a very large output per pole; the cooling surfaces are therefore small in comparison with the volume of active material and the amount of heat liberated therein; and efficient ventilation can only be obtained by a carefully arranged system of forced draught. Mechanically, a serious problem arises from the large rise of speed in the event of the governor gear failing to respond to a sudden removal of the load. While the dimensions of the machine must be sufficient to give the rated output at the normal speed, the rotor must be capable of carrying from three to four times the normal rotational forces, with an adequate margin of safety.

At the present time, almost universally, the energy is generated as alternating current, on account of the simplicity and reliability obtained with a moderate generating pressure, which is readily transformed to the highest pressures which may be required for economical transmission. Occasionally, however, the advantages of high-tension *direct-current* transmission may outweigh the essential difficulties of its generation. This question is discussed, in connection with the Thury system of transmission, in Chap. XI, p. 247.

Of alternating-current generators there are the *synchronous* and the *asynchronous* (induction) types. In recent years the latter have come into practical use, especially for automatic stations, on account of their robustness of construction and simplicity in operation. The construction and properties of the asynchronous generator are described in Chap. IV. The earlier synchronous alternators were frequently built of the "inductor" type. Both armature and exciting windings were stationary, and the only revolving part consisted of a solid steel wheel with projecting lugs or poles.* Such an arrangement was manifestly suited to the high peripheral velocities and "run-away" speeds of water-wheel practice; but experience has shown that these advantages were less important than those of the salient-pole *revolving-field* type, with which, therefore, the succeeding sections will be almost entirely concerned.

Two principal arrangements of the generating unit may be distinguished; namely, the "vertical-shaft" and the "horizontal-shaft" types. The former is adopted most frequently with the low-head reaction turbine, the latter with the high-head impulse turbine or Pelton wheel; but these conditions are sometimes reversed. The smaller generators are more economically built for a horizontal shaft, since this allows of the simplest scheme of ventilation and often enables a standard engine-type machine to be used. In larger sizes, also, the horizontal type will be preferable when an additional fly-wheel has to be added, since such extra weight cannot so conveniently be carried on the thrust bearing and bearing supports of the vertical type. The very important considerations of floor-space are dealt with later. In the great majority of cases, the choice of the horizontal or the vertical type will depend upon hydraulic considerations.

In the older generating plants, where the units were of small output, a moderately high speed horizontal-shaft generator was often driven by a low speed vertical-shaft turbine, through bevel gearing. This was a satisfactory arrangement, and one which may still be adopted with advantage in special circumstances calling for small low-head units. The generators are of the simple "open" type, and need no special conditions.

2. Frequency and Number of Phases.—The question of the most desirable *frequency* for an electrical power supply is one which has been discussed repeatedly and at great length; and it is here possible only to summarize the more important considerations. Fortunately, the practical problem is simplified by the fact that in most countries two frequencies—a high and a low frequency—have become recognized as standard. In the United States and Canada, either 60 or 25 cycles per second is now almost universally adopted; on the Continent, 50, $16\frac{2}{3}$, and 15; in Great Britain and in South America, 50 and 25 cycles per second. Generally, it may be said that the high frequency is the more suitable for lighting purposes, the low frequency for the transmission of power. In the utilization of the power, however, while the lower frequency is preferable when synchronous converters are

* For a detailed discussion of the inductor alternator, see Hawkins and Wallis, *The Dynamo*,

to be used for transformation to direct current (on account of the greater distance then obtained between consecutive brush-arms on the commutator), the higher frequency has a distinct advantage when induction motors are to be used, since a greater number of speeds within the useful range are then possible. The speed of a synchronous machine having p pairs of poles, and working on a system of frequency f cycles per second, is given by: $n = 60 f/p$ revolutions per minute. Thus, ignoring 2-pole machines as being of special and expensive construction, the available motor speeds above about 300 revolutions per minute are (allowing about 4 per cent slip):

INDUCTION MOTOR SPEEDS

Number of Poles.		4	6	8	10	12	14	16	18	20	22	24
Motor speed in r.p.m. at	60 ~	1720	1150	860	685	575	490	430	380	345	310	290
	50 ~	1430	960	720	575	480	410	360	320	290		
	40 ~	1150	765	575	460	380	330	290				
	25 ~	720	480	360	290							
	$16\frac{2}{3}$ ~	480	320									
	15 ~	430	290									

Except with frequencies below 25 cycles per second, the limitation of the speeds available for the generator itself is not serious. When it is required to change from a low to a high frequency, or vice versa, by means of a synchronous motor-generator set, as where both lighting and power services are required, the system with 60 and 25 cycles per second allows only of a speed of 300 revolutions per minute, the two coupled machines having 10 and 24 poles. By the use of an induction motor with a suitable slip, coupled to a synchronous alternator, several other speeds will be found possible.

As regards the generator itself, for a given speed, a lower frequency involves fewer poles, and therefore a greater output per pole. Owing to the greater mass of active material per pole, the efficiency of cooling is impaired; and low-frequency machines are therefore heavier and more expensive than high-frequency machines of similar output. The coils of both stator and rotor are larger on the low-frequency generators; the short-circuit forces are greater; and the effective clamping of the windings is more difficult. Similar remarks apply also to the transformers; at low frequencies the weight of the core is greater, and the conditions on sudden short-circuit more severe. These difficulties can, however, be effectively met; and are usually unimportant in comparison with the advantages of a low frequency in reducing the charging current and pressure-drop in the transmission line, and thereby increasing its current-carrying capacity. For alternating-current railway work the lowest frequencies are essential.

As regards *the number of phases*, there is little freedom of choice, the question being largely determined by the nature of the load to be supplied. Single-phase supply, although offering some advantage in simplicity of equip-

ment, involves increased losses in the generators, additional complication of the rotating element (see p. 79, *damping windings*), and generally less reliable performance. This system is only used when absolutely essential, as for direct supply to alternating-current railways using commutator motors.

Of the polyphase systems, the three-phase is preferable to the two-phase for general power purposes, since the plant is more fully standardized and therefore cheaper. Moreover, where a single-phase load (as for lighting) has also to be taken from the polyphase mains, a three-phase system is less liable than the two-phase to become seriously unbalanced, resulting in extra heating of the generators. On two-phase circuits, unless solely applied to polyphase motors, a possible difference of 25 per cent between the currents of the two phases should be anticipated; and suitable provision should be made in the generators to meet this condition without injurious heating. Rotary converters are smaller, more efficient, and give much better commutation on three-phase than on two-phase systems. When the energy is to be converted to direct current within the generating station, six-phase generators and converters are still more advantageous.

3. **Voltage.**—For distribution within a short radius of the power house, the voltage of generation and transmission will be the same as that required for the supply to consumers; but for transmission to greater distances, for which the energy is transformed to extra high tension, there is a wide choice of the voltage of generation. An unduly low voltage involves heavy and expensive bus-bars and switch-gear; and in large units offers difficulty in the construction of the low-tension windings of the transformers and the stator windings of the generators. A very high voltage, on the other hand, requires a winding with many wires in series per slot; a greater thickness of insulation, resulting in a hotter and mechanically weaker winding; and generally reduced reliability. The loss of space in insulation also increases the size and initial cost of the machine.

From the point of view of the robust and efficient construction of the generator, it is desirable to have *two* conductors per slot (see p. 68, *diamond-coil windings*); and the stator current should then vary from 300 or 350 amperes in the smallest machines, to 800 or 1000 amperes in the largest. It may thence be readily deduced that the most suitable voltage of generation, when not otherwise restricted, should vary—for a three-phase machine—approximately as follows:

Output	..	200	500	1000	2000	5000	10,000	15,000 kw.
Pressure	..	450	900	1500	2500	5000	9,000	11,000 volts.

The power-factor is here assumed to be 0·8, and the voltages given are the interlinked line pressure (i.e. $\sqrt{3}$ times the phase pressure between line and neutral point). For two-phase machines, the phase pressure should be about $\sqrt{\frac{3}{2}}$, or 0·87 times the above values.

There may, of course, be cases in which a local supply of power is required,

in addition to the main extra-high-tension system; and the generator voltage may be determined by such requirements. Where rotary converters are installed within the power station, for the bulk supply of direct current, generators of moderate power may be wound to give the necessary voltage direct; but with very large outputs this is usually impossible, owing to the large number of conductors in parallel that is required, and the complication involved in preventing excessive circulating currents between these.

CHAPTER II

Electrical Characteristics

Open-circuit characteristic; short-circuit characteristic; sudden short-circuit; inherent regulation; fly-wheel effect; parallel working; wave-form.

1. The electrical performance of a synchronous alternator in respect of regulation on load, may be expressed, with sufficient accuracy for practical purposes, in terms of its characteristics on open-circuit and on short-circuit. Under these two conditions the power output of the machine is zero; and the two characteristics are therefore conveniently and economically determined by tests on the actual machine. In the course of design they form, likewise, the simplest cases for calculation. In the following sections the general significance of these two characteristics, and their determination by tests, will be considered. Methods of calculation from the dimensions of the machine are naturally of too specialized a nature to permit of useful treatment in the space here available; but references are given to standard works where the various questions are thoroughly discussed.

2. Open-circuit Characteristic.—The "open-circuit" or "magnetization" curve represents the relation between the exciting current and the terminal voltage, when the machine is run at normal speed and is delivering no external current, i.e. with all terminals open-circuited. The form of this curve depends upon the magnitude of the flux required to induce any given voltage, as determined by the number and arrangement of the stator conductors; and upon the number of ampere-turns required upon the field-magnet to produce such a flux, this involving the dimensions and materials of the various parts of the magnetic circuit.

The active flux is given by the expression

$$E_{ph} = 4{\cdot}44 k_w T \Phi f \times 10^{-6}, \qquad (1)$$

in which E_{ph} denotes the phase pressure in volts, T the number of turns per phase in series, f the frequency in cycles per second, Φ the active flux per pole in megalines (i.e. millions of c.g.s. lines), and k_w is a "winding factor"

depending upon the arrangement of the stator winding.* This factor is the product of two components: the *distribution factor*, involving the angle occupied by the coil-sides of one phase in each pole; and the *coil-span factor*, depending upon the average span of the coils as compared with the full pole-pitch. If s denote the fraction: slot-pitches covered by phase-band $\div$ slot-pitches per pole, then the distribution factor is

$$\frac{\sin s\pi}{s\pi};$$

while the coil-span factor is given by

$$\sin\frac{\pi}{2}\left(\frac{\text{slot-pitches spanned by mean coil}}{\text{slot-pitches per pole}}\right).$$

For numerical values of these expressions, see Art. 8, p. 22.

The flux Φ has to pass through the air-gap, the stator teeth, and the stator

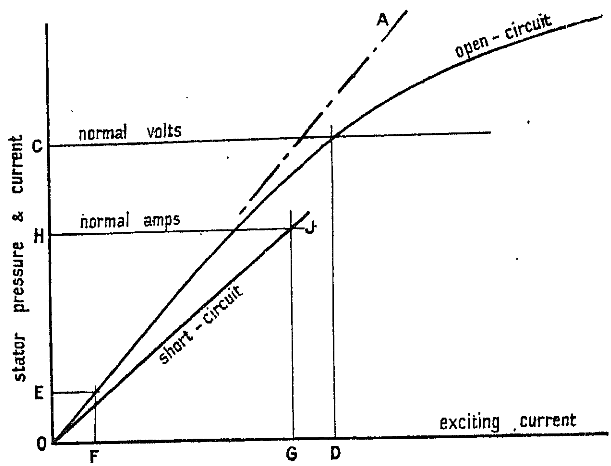


Fig. 1.—Open-circuit and Short-circuit Characteristics

core. The flux in the poles and yoke of the field magnet is 10 to 20 per cent greater, on account of flux leaking between the adjacent poles without entering the armature. The ampere-turns required to produce the flux in the air-gap is, in any one machine, proportional to the magnitude of the flux; and if no excitation were required for the remainder of the magnetic circuit, the relationship of terminal volts to exciting current would therefore be shown by a straight line, OA (fig. 1), which is consequently termed the "air line". The effect of the reluctance of the iron parts of the circuit is to add to the necessary excitation an amount which, above a certain point, increases rapidly with the voltage induced; thus, the open-circuit curve bends over as shown by the line OB. The actual shape of the curve depends

* For more detailed information, and in special circumstances, see S. P. Smith and R. S. H. Boulding, "The Shape of the Pressure Wave in Alternating-current Machinery", *Journal I. E. E.*, Vol. LIII, pp. 214–?

upon the magnetic densities in the various iron parts of the circuit;* and, together with the height of the working voltage OD relatively to the bend of the curve, determines the variation of voltage produced by a given change in excitation.

The possible densities of the flux in the laminated parts, which carry an alternating flux, are strictly limited by considerations of the losses and heating produced; the stator core and teeth, therefore, usually contribute only in a minor degree to the bending of the open-circuit curve, except in 25-cycle and still lower frequency machines. The shape is due principally to magnetic saturation of the poles and of the magnet wheel or yoke, although the latter has often to be designed from quite other points of view.

In making an open-circuit test, the machine is run at the normal speed, where that is convenient, and the voltage at the terminals, corresponding to a range of values of the exciting current, is measured. The readings should be carried to about twice the excitation OC at which normal voltage is attained. The voltage can be measured either between lines (when the phases are interlinked at a neutral point), or across one phase (between line and neutral), as may best suit the instruments available; but it is always advisable, on a salient-pole machine, to check the ratio of phase volts to line volts at a low point on the curve, and again at one of the highest points. It is seen from equation (1), that the test can equally well be made at any lower known speed and frequency, and the measured pressure increased proportionately to correspond with normal speed. This is often convenient when the power required to drive the machine at the highest voltage is greater than can be supplied, as in testing at the makers' work; or where the full voltage would exceed the range of the testing instruments available.

3. Short-circuit Characteristic.—The "short-circuit line" shows the relation between the exciting current and the armature current when the machine is run with its terminals short-circuited. Under such conditions the passage of the stator current absorbs a small pressure representing the resistance and leakage reactance of the stator winding. The resistance includes the effective increase due to eddy currents in the conductors, or otherwise associated with the winding, and may be 10 to 20 per cent greater than the resistance measured by direct current. The leakage reactance is due to flux surrounding and linked with the conductors, both in the slots and in the overhang or end connections. Its magnitude depends upon the length of the conductors, the number of conductors assembled in a group, and the disposition of the several groups. The reactance is difficult to estimate theoretically, and can only be obtained satisfactorily from test results on other machines of similar constructional arrangement. The induced pressure required to overcome the reactance drop at full-load current is usually expressed as a fraction of the normal voltage; this ratio represents also the relation which the leakage flux, at full-load current, bears to the main flux at normal voltage. As an approximate rule, this fraction may be taken as 10 to 15 per cent; it is thus 5 to 10 times as great as the pressure-

* See Hawkins and Wallis, *The Dynamo*, 5th ed., Chap. XV.

drop due to resistance; and the latter may be ignored in connection with the short-circuit characteristic.

On short-circuit, then, there must exist in the stator core a flux equal to the leakage flux, and to produce this an exciting current OF (fig. 1) must be supplied. At the same time, the current-carrying conductors of the armature exercise a demagnetizing effect upon the magnetic circuit—the true *armature reaction.* The effective value of this reaction is given, in ampere-turns, by

$$F_1 = \frac{18}{\sqrt{2}\,\pi^2}\,quI,$$

where q denotes the number of slots per pole per phase, u the number of conductors in series per slot, and I the current in each conductor; whereas the effective value of an exciting current I_e on the field magnet is

$$F_1 = \frac{4}{\pi}\sin\beta\frac{\pi}{2} \times T \times I_e,$$

in which β denotes the ratio of pole-width to pole-pitch, and T the number of turns per pole on the field-magnet. Hence, to neutralize the armature reaction, the field-coils must carry the additional excitation

$$I_e = \frac{1{\cdot}01}{\sin\beta\frac{\pi}{2}}\,\frac{quI}{T}, \qquad\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which is represented by FG. The total current, OG, then gives the actual excitation required to produce full-load current OH on short-circuit. Since the resultant flux is small, there is little saturation of the magnetic circuit; hence, both the leakage reactance and the true armature reaction are proportional to the stator current, and the short-circuit characteristic is a straight line OJ. If, at high values of the current, the leakage paths become somewhat saturated, the short-circuit line bends slightly upwards; while if saturation of the main magnetic circuit commences, the line bends slightly downwards.

In making the test, each phase may be individually short-circuited, or the several phases may be connected in " star " and the terminals short-circuited through current transformers, while a set of readings of corresponding stator and rotor currents is taken. It is clear that the leakage reactance voltage is proportional to the frequency (or speed), as also is the pressure induced by the excitation OD; hence, it is quite unnecessary that the machine be run at normal speed, or, in fact, that any reading of the speed be taken.

4. Sudden Short-circuit.—The conditions obtaining when a machine running at full voltage, either on load or on open-circuit, is suddenly short-circuited near its terminals, are entirely different from the conditions of steady short-circuit (Art. 3), in which the main flux is greatly limited by armature reaction. For, at the instant of a sudden short-circuit, there is in the magnetic circuit a large flux corresponding to the full voltage; and

although a large demagnetizing action be instantly produced, the flux can diminish only comparatively slowly, being sustained by large eddy-currents, set up by its slow diminution, in all solid metal parts of the magnet wheel and in the exciting circuit. Immediately after short-circuit, therefore, the alternating current rises to such a value that the whole of the normal induced pressure is absorbed by the leakage reactance; that is, to the value OH × OC/OE; or

$$\frac{\text{full-load current} \times 100 \text{ per cent}}{\text{percentage reactance}}.$$

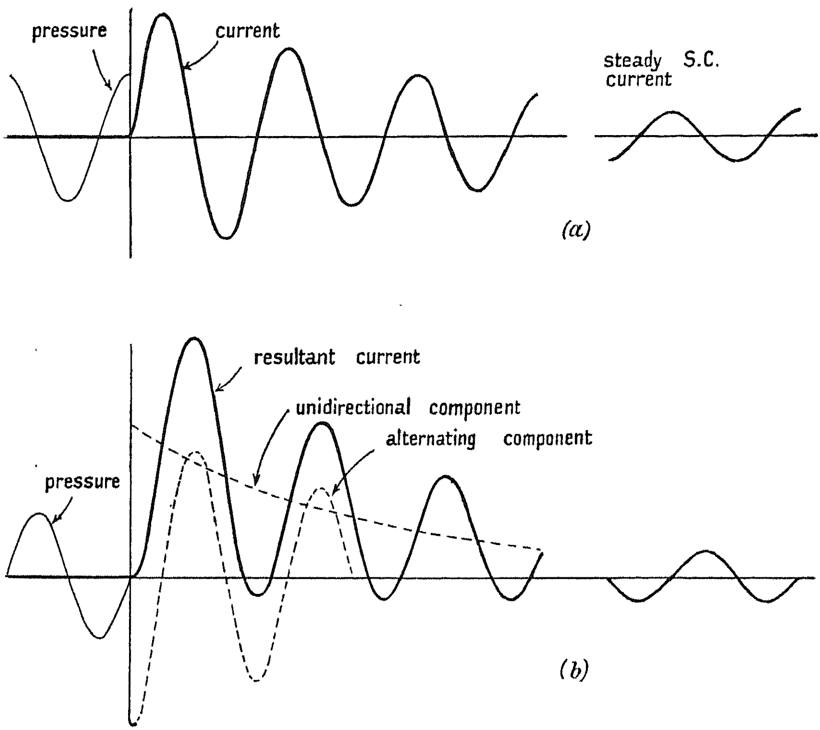


Fig. 2.—Sudden Short-circuit Current. (*a*) Symmetrical; (*b*) unsymmetrical.

As energy is absorbed by the eddy currents, the main field gradually diminishes under the demagnetizing effect of the armature reaction, and with it the stator current; until, after a period of several seconds, the conditions of *steady* short-circuit obtain. These phenomena are illustrated in fig. 2 (*a*), for the case when short-circuit occurs at the instant of maximum voltage, so that current and voltage have initially the phase relationship appropriate to an inductive circuit. If, however, the circuit is closed when the voltage is zero, there is superposed upon the alternating current a unidirectional current of the same amplitude, in order to fulfil the condition of zero current at the instant of short-circuit (see fig. 2 (*b*)). The unidirectional component gradually subsides as energy is absorbed in the

passage of the current through the stator windings; so that while the alternating component diminishes as in fig. 2 (*a*), the curve gradually becomes symmetrical about the time axis. It is of the greatest importance, therefore, in describing the performance of a machine on sudden short-circuit, to state which of the cases *a* and *b* is considered; and which ordinate of the curve is referred to. The simplest basis for comparison is to state the root-mean-square value of the first half-wave in the symmetrical condition, fig. 2 (*a*); namely, that given by the formula above. The maximum amplitude is $\sqrt{2}$ times the value so expressed. The greatest possible instantaneous current—the amplitude of the first half-wave in the unsymmetrical condition, fig. 2 (*b*)—is twice as great; but the root-mean-square values clearly do not bear this simple relationship, and in the latter case are of little practical significance.

The actual performance of a machine in this respect can be obtained from a calibrated oscillogram of the current at the instant of short-circuit; but there is much practical difficulty in synchronizing the closing of the switch with the operation of the oscillograph camera. It is usually sufficient, from the practical point of view, to confirm that no damage to the generator windings results from such short-circuit, repeated several times to give greater probability of obtaining a case of maximum dissymmetry. Every generator should withstand this test without the slightest trace of movement or of injury to the coils. The test is made on open circuit, and the terminal voltage should be raised so far above the normal pressure as to obtain the same flux in the core as under full-load conditions (see Art. 5).

If under the conditions of operation there is a possibility of a generator being accidentally paralleled with the wrong polarity, on to bus-bars on which many other machines are already working, the momentary currents produced may reach practically twice the values already considered. It is doubtful whether any construction of the windings can be depended upon to withstand the severe stresses then occurring; and where such conditions are to be expected, the reactance of the generating unit should be at least doubled, by means of an air-core choking-coil permanently connected in series with the stator winding.

In the specification of machinery, it is preferable to allow the manufacturer some latitude in design, rather than to restrict the short-circuit current too severely. It is possible to make various arrangements of the coil groups which limit the instantaneous current without diminishing the forces on the windings; while again, a more reliable machine may be obtained by bracing the windings so firmly that they will withstand a fairly high short-circuit current, rather than by increasing the reactance by artificial devices.

5. Inherent Regulation.—The question of *regulation* is one of the most important in the selection of the generating plant. The regulation of the station as a whole determines the constancy of frequency and voltage; while upon the relative regulation of the individual machines depends the uniformity with which the load is shared between them. The latter aspect of the problem is deferred for consideration in Art. 7.

From equation (1) it will be seen that the voltage depends equally upon two variable factors: the flux Φ and the speed n. It is therefore necessary to consider separately the *inherent regulation* of the alternator, or the variation of the terminal pressure with the load, and the *speed regulation* of the turbine; the latter also determines the variation of frequency.

From the open-circuit and the short-circuit curves (fig. 3), the necessary excitation under any condition of load may be predicted, and thence the inherent regulation. Let the line OE (fig. 3) represent the terminal voltage to be maintained, OI the external load current, and the angle EOI the angle of lag, i.e. cos EOI is the power factor of the load. Now the reactance voltage OE (fig. 1) corresponds to the normal full-load current OH; hence EF (fig. 3), drawn perpendicular to OI, is made equal to OE $\times$ OI/OH; and the line OF shows the total induced pressure, both in magnitude and in

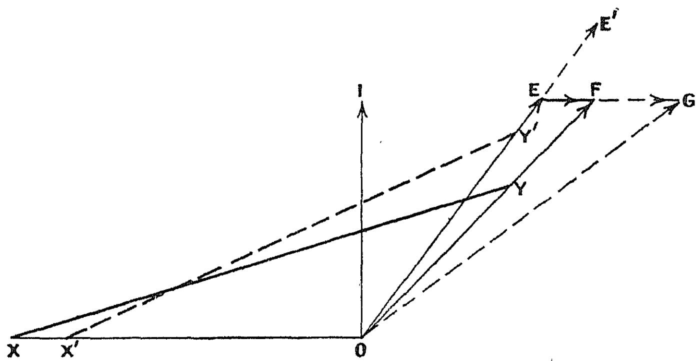


Fig. 3.—Excitation on Load

its phase relation to OI. The resultant excitation necessary to produce this pressure is read off from the OC curve, and marked off along OX, at right angles to OI. Similarly, the armature reaction, FG (fig. 1) corresponds with the normal full-load current; hence with the particular load OI the reaction is OY = FG $\times$ OH/OI, and is set off along OF (fig. 3). The line XY then gives approximately the excitation required on load. The voltage OE′, which the excitation XY would produce on open-circuit, is read off from the open-circuit curve; then EE′ is the *rise of voltage* upon throwing off the load OI at the lagging power factor cos EOI, while the exciting current remains constant. The *inherent regulation*, expressed as a percentage of the normal voltage, is thus 100 per cent $\times$ EE′/OE.

It is necessary to distinguish between the *rise* of voltage upon removing the load from an alternator working on full-load and excited to normal voltage, and the *drop* of voltage upon suddenly applying a similar load to a machine running on open-circuit and excited to normal voltage. Under the latter conditions the terminal pressure may be reduced almost to zero. It will be seen from fig. 1 that, if OG be greater than OD, the normal open-circuit excitation will not produce full-load current even on short-circuit, or at zero terminal pressure. It is possible, however, to consider both the rise and

fall of pressure consequent upon a given *small change* of load in either direction, when the machine is already working on load and excited to normal terminal pressure. Owing mainly to the curvature of the open-circuit characteristic, the drop in pressure is always greater than the rise in pressure accompanying an equal change in current output.

In the above method of estimating the excitation on load, it will be evident that the leakage reactance need not be known with any great accuracy; for the manner in which the total short-circuit exciting current is divided between the effects of leakage and true reaction has little influence upon the final result. Extending this argument, the distinction between the two components may be ignored; and the very simple construction indicated by a dotted line in fig. 3 may be employed. Here OY′ is made equal to OG × OI/OH, and OX′ equal to OD of fig. 1; X′Y′ is then required total excitation. This result, however, is definitely too low, by an amount which varies with both load and power factor; but with the addition of about 10 per cent to the length of X′Y′, the method is sufficiently accurate for most practical purposes, and is one most readily applied to test results, without the inconvenience of resolving the observed short-circuit excitation into its two components by the use of equation (2) and the constructional data of the machine. In fact, no methods of the kind here described can be closely accurate, because (1) the increased leakage between the poles on load is not taken into account in using the open-circuit magnetization curve; and (2) with salient poles there is no theoretical justification for combining OX and OY directly as simple vectors.

By repeating the graphical construction for a number of values of the current and power factor, it is a simple matter to plot a set of curves, such as fig. 4, showing the exciting current necessary to maintain normal voltage under various conditions of load. These again may be converted into curves, such as fig. 5, which show the rise of pressure upon throwing off any given load while the exciting current is held constant. It will be evident from fig. 5 that the rise in pressure corresponding to a given reduction in *current* output increases rapidly with diminishing (lagging) power factor; consequently the rise in voltage, upon removing a given load in *kilowatts*, varies still more rapidly with the power factor. The required inherent regulation of an alternator is usually specified as the percentage rise in pressure, from normal voltage, upon throwing off full-load kilowatts (1) at the normal working power factor, (2) at unity power factor. The latter alone is sometimes stipulated, since it admits of direct verification by loading the generator on a non-inductive resistance.

The inherent regulation will have been seen to depend upon (1) the leakage reactance; (2) the ratio of the armature reaction to the excitation expended upon the reluctance of the magnetic circuit (i.e. FG/OD); and (3) the position of the working point on the open-circuit curve. The limits within which the first quantity can be varied are quite narrow; and it must be regarded in any case as a necessary provision for limiting the severity of the sudden short-circuit forces. The regulation, however, cannot in any case be less

than $\frac{(OF - OE)}{OE} \times 100$ per cent (see fig. 3); and its excess over this value is attributable to the factors (2) and (3) above. A given closeness of regu-

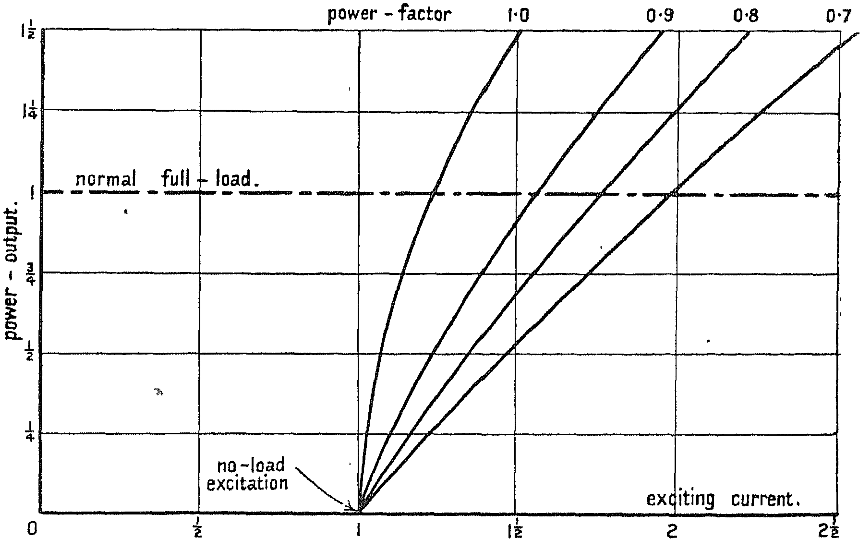


Fig 4.—Variation of Exciting Current with Load for constant Terminal Pressure

lation may be obtained either by taking the working point near the straight part of the curve and using a weak armature (i.e. a small ratio of FG/OD), or by working at a higher point on the curve with a strong armature (large ratio of FG/OD). The former method results in a large and expensive machine, but one having a large overload capacity, since the excitation increases comparatively slowly with the load. The latter design gives a smaller and cheaper machine, in which the active material is used more efficiently; but the overload capacity

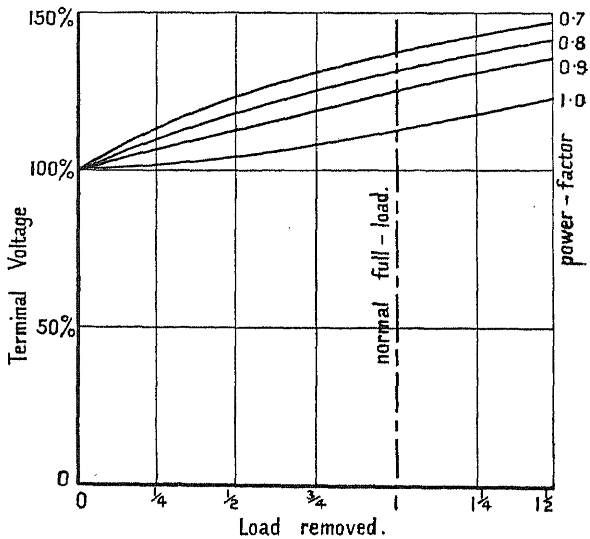


Fig. 5.—Inherent Regulation for various Conditions of Load

is more limited. The combination of the two principles in a suitable proportion, therefore, depends upon the required provision for overload; but it

will be evident that, from either point of view, a more economical and more efficient machine is obtained by sacrificing closeness of regulation. A further argument is found in the fact that, in nearly all cases, an automatic voltage regulator is essential on account of the speed variations of the turbine, and close inherent regulation in the generator is then of no further advantage.

As also in the question of the variation of speed, it is necessary to distinguish between the instantaneous and the permanent voltage variation following a change of load. The instantaneous variation is only that corresponding to the leakage reactance, i.e. OF — OE in fig. 3, and the greater variation OE′ — OF, involving a change in the main flux, may occupy an interval of several seconds, depending upon the size of the poles. The time-lag is affected considerably by the design of the magnetic circuit, being prolonged by the use of solid, rather than laminated, poles or pole-shoes, and by any closed metallic circuit of low resistance which surrounds the path of the main flux.

The total variation can, of course, be found accurately from the open-circuit curve, if the actual excitation required on normal load and power factor can be determined by a direct test on load; but any question of the rapidity of regulation can clearly only be settled by the often inconvenient procedure of suddenly throwing off the load. If it is possible to remove suddenly a practically wattless load, the *instantaneous* part of the voltage rise gives a measure of the reactance voltage, and thus permits a reliable prediction of maximum current on sudden short-circuit.

6. Fly-wheel Effect.—The second factor entering into the voltage regulation, namely, the *change of speed* accompanying a variation of load, is entirely a mechanical question. It is to be particularly noticed that the change of speed is determined by the change of true power output, whereas the inherent voltage regulation of the generator is far more affected by a change of wattless current than by an equal change of power current. Again, it is essential to distinguish between the *instantaneous* variation of speed which immediately follows the change of load, and the smaller *permanent* variation which remains after an interval of some seconds. The latter depends solely upon the characteristics of the governor mechanism, and represents the difference of speed which practically is necessary to cause the governor mechanism to move from the " closed " to the " full-gate " position. The former effect, however, depends upon the rapidity with which this change can take place, and upon the amount of kinetic energy stored in the revolving system. The momentary rise in speed upon throwing off full load is directly proportional to the time occupied by the governor in moving over its full range, and inversely proportional to the amount of stored energy. The rapidity of action may be simply a question of the promptness with which the governor gear can be made to respond to a change of speed; but in other circumstances it becomes primarily a hydraulic problem, involving the retardation or acceleration of the moving mass of water.*

* The actual calculation of the necessary amount of stored energy is discussed in Vol. I,

The total kinetic energy of a generating unit is derived from the following components:

(1) the turbine runner, or bucket wheel;
(2) the revolving mass of water within the runner (in the reaction-turbine);
(3) the rotor of the generator;
(4) a separate fly-wheel added to the shaft.

In addition, however, the effective kinetic energy includes a large part of the stored energy of all other rotating machinery connected to the system, apart from that of the generating units; and to the above list it may therefore be necessary to add:

(5) motor-driven fly-wheel set;
(6) rotary converting apparatus connected to the system.

The items (1) and (2) usually contribute so small a fraction of the total energy, and are so closely determined by the hydraulic design, as to admit of no useful artificial increase. Item (6), however, has often a very considerable effect, and its neglect may lead to the use of too large an amount of stored energy in the generators, increasing the initial cost, and attended by extra losses in bearing friction and windage.

The rotor of the generator forms one of the largest items, and can nearly always be made to yield all the energy required in addition to that provided by items (1), (2), and (6). The kinetic energy of the rotor is proportional to its moment of inertia and the square of the speed of rotation; the numerical relationship being as follows:

$$\mathrm{E} = 0{\cdot}00017\ \mathrm{I}n^2\ \text{lb.-ft.},$$

where n is the speed in revolutions per minute, and I is the moment of inertia (or the total mass multiplied by the square of the radius of gyration*) expressed in lb.-feet². The moment of inertia, or *fly-wheel effect*, varies greatly with the diameter of the rotor, which in turn is limited by the speed of rotation; the question of stored energy has therefore to be considered at the outset in the design of the generator, as well as in the choice of the normal running speed.

The kinetic energy of a rotor of diameter D and axial length L, running at a speed of rotation n, is theoretically proportional to

$$\mathrm{D}^4\mathrm{L}n^2;$$

but actually is more nearly given by

$$\mathrm{E} \propto \mathrm{D}^{3\frac{1}{2}}\mathrm{L}^{\frac{3}{4}}n^2,$$

on account of changes in the proportions of the wheel that are necessary with change of diameter. Again, the rated output of the generator may be expressed in the form

$$\text{K.V.A.} = \mathrm{C} \times \mathrm{D}^2\mathrm{L}n,$$

* With the metric system of units, fly-wheel effect is often stated conventionally as the product of the total mass into the square of *twice* the radius of gyration (or GD^2).

where C is an "output coefficient", which increases with the diameter and speed, but diminishes somewhat with increasing length, owing to the effect of these variables upon the ventilation of the machine; so that, approximately,

$$\text{K.V.A.} \propto D^{2\frac{1}{2}} L^{\frac{3}{4}} n^{1\frac{1}{4}}.$$

Hence $$E \propto \text{K.V.A.} \times D n^{\frac{3}{4}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Thus, for a given rated output, the stored energy may be increased by using a rotor of large diameter and small axial length; but the possible diameter is limited by other important considerations.

In any case the maximum diameter is determined by the rotational stresses. The stress in any part is proportional to the square of the diameter and the square of the angular speed; so that, for given limits of safe stress, the greatest permissible diameter varies inversely as the speed.* Hence, the stored energy can never exceed the value given by

$$E \propto \text{K.V.A.}/\sqrt{n}.$$

It will be seen that, in the absence of any other restriction of diameter, the possible stored energy for a given output-rating diminishes with increasing speed. For this reason it is necessary, in high-speed machines, to adopt the strongest forms of rotor construction (see Arts. 5, p. 62, and 6, p, 64), so as to increase as far as possible the maximum diameter for the given speed.

At low speeds of rotation, on the other hand, it would usually be a simple matter to provide the required kinetic energy if it were always feasible to increase the diameter to the limit set by considerations of stress. There are often, however, serious objections to so doing. The cost of both stator and rotor is increased, owing to the difficulty in obtaining sound castings or other materials of very large size, and in machining, handling, and testing. There may also be limitations in transport, for while the stator frame can be satisfactorily built in segments, the rotor cannot be so treated. The most serious disadvantage, however, is in the large floor-space required, which involves increased cost of the masonry foundations, and often an enlargement of the entire building. For these reasons, the peripheral velocity and stress are generally much lower in low-speed than in high-speed machines, to such an extent, in fact, that the regulation of low-speed units is commonly found to be inferior to that of the higher-speed sets. This is particularly the case with low-head vertical-shaft units, where the necessary diameter would require an excessive floor-space; and where also an equivalent increase in the mass of the wheel, as by an additional rim or fly-wheel, may offer much mechanical difficulty. In such circumstances, the device has sometimes been adopted of placing the revolving field-magnet outside the stationary armature, giving what is known as the "umbrella" type of machine. In this way the best possible use is made of the maximum diameter available, and from the point of view of regulation

* In this connection it is to be noticed that the speed by which the diameter is limited is the maximum "overspeed" of the set; and the fly-wheel effect may be increased if the percentage overspeed can be reduced.

the arrangement may meet all requirements. The ventilation of the machine, and in particular the cooling of the internal armature, becomes so difficult, however, that this scheme is only economically feasible where, for other reasons, the armature has in any case to be of exceptionally liberal design. Notable examples of this type of machine are the 6250 K.V.A., 300-r.p.m. alternators installed in the power house of the Niagara Falls Electric Power Company.

Using, then, the largest diameter permitted either by the rotational stress, manufacturing facilities, or floor-space, further increase of fly-wheel effect is only to be obtained by the addition of mass; that is, by increasing either the axial length or the radial thickness of the pole-yoke or rim. Extension of the length of the rim soon commences to interfere with the ventilation of the machine, especially in the open slow-speed naturally ventilated type with which the inertia difficulty most often arises. If, on the other hand, the radial thickness of the rim be increased, the material thus added at a small radius is not very effective, while adding to the bearing friction, to the initial cost, and to the difficulty of casting and machining; and a point is soon reached at which it is more economical to adopt a separate fly-wheel. The maximum effective increase in mass obtainable in this way is limited practically to about 25 per cent above that required by the magnetic design of the field-magnet.

Very frequently, however, a fly-wheel effect several times as great as that given by the normal design of the alternator is required. A separate fly-wheel is then essential. When the necessary added weight is not very great as compared with the weight of the magnet wheel, the most economical arrangement—often particularly convenient with an open-type machine—is to mount the fly-wheel directly adjacent to the rotor, and between the same bearings. It is important then to consider the effect of the centrifugal windage of the fly-wheel upon the ventilation of the alternator. By a judicious arrangement of the air-paths and end-guards, it is possible to obtain a distinct improvement of the ventilation from a fly-wheel which might otherwise be a serious obstruction to the natural axial flow of air to the machine. When the weight to be carried is large, and particularly with enclosed machines, it is usually preferable to mount the fly-wheel on a separate span of the shaft, provided where necessary with an additional pair of bearings. This arrangement gives complete freedom to use the strongest possible form of fly-wheel, allowing an increase in the effective peripheral velocity, and thus a minimum total weight. With such forms as the solid plate wheel, there is practically no limit to the fly-wheel effect obtainable in this way.

Where a specially large fly-wheel effect is required, there may be considerable advantage in using a separate "fly-wheel set", driven by a synchronous or induction motor. This arrangement is also a convenient alternative in cases where the addition of a fly-wheel to the alternator shaft offers special mechanical difficulties, as often in low-speed vertical units. A separate fly-wheel set, moreover, can be disconnected from the system during

periods when its assistance is not actually required, and thus its driving power eliminated. Since there is almost a free choice of speed for a fly-wheel set, limited only by the motor speeds available (see table, p. 3), a high speed is employed, so as to reduce the diameter of the wheel and the floor-space occupied. The strongest forms of wheel are available (such as rolled steel plates, possibly without a central hole), allowing the use of the highest peripheral speeds, and a reduction of the cost, weight, and driving losses to a minimum.* The heating of the driving motor, upon which its size and cost principally depend, is only that corresponding to the short-duration loads represented by the energy absorbed or given out by the fly-wheel; but the motor must be designed to carry an exceptionally heavy maximum torque (i.e. the armature must be weak as compared with the field magnet) to ensure that it will remain in synchronism with the generator under the maximum torque which the fly-wheel may exert.† When a synchronous motor is used, it requires also an efficient damping winding for self-starting as an induction motor; but this requirement is not as a rule unduly severe, especially if provision is made for "flooding" the fly-wheel bearings before starting. It is, further, often convenient to use the motor, when of the synchronous type, to carry a portion of the wattless load of the station. Although this needs a machine capable of carrying a continuous—rather than an intermittent—load, and with a specially heavy field winding, the extra size and cost may be inappreciable as compared with the advantage of obtaining a greater true power load from the main generators. A particularly beneficial arrangement is obtained by installing the fly-wheel set at the receiving end of the transmission line, where, by relieving the line of wattless current, it may increase the power-carrying capacity very greatly.

Finally, to determine the *resultant regulation* of voltage, it is only necessary to take the product of the inherent voltage variation of the alternator and the speed variation of the combined unit; and since the two effects follow different laws as regards time interval, the process is most conveniently carried out graphically. The total variation cannot be so far reduced economically that an automatic voltage regulator can be dispensed with; and where this apparatus is employed, a practically steady voltage is maintained by field-adjustment following instantly upon the commencement of any voltage variation, whether arising in the generator or the turbine. Speed regulation then is of importance only as regards variations of *frequency*. This is comparatively unimportant in the majority of power-supply systems, since the variations are not so rapid that synchronous machinery is liable to drop out of step; nevertheless, there are some applications, such as the supply to motor-generator sets converting to direct current, where frequency variation is even more objectionable than voltage variation. It is thus the necessary uniformity of frequency, rather than of voltage, which must determine the fly-wheel effect required.

* This method is closely analogous to the use of the fly-wheel on the motor-generator set of an electric rolling-mill equipment; and the advantages, as compared with a fly-wheel mounted direct on the slower-speed main shaft, are identical in the two cases.

† See p. 22.

7. Parallel Working.—The conditions in the parallel working of water-wheel units are simple, and the performance is usually quite satisfactory. This is due, of course, to the fact that the turning-moment of the hydraulic turbine is uniform; so that oscillation or phase swinging of the alternators, which arises with engine-driven generators owing to cyclic irregularity of driving torque, is here of no importance. Damping windings are consequently only fitted when required from a consideration of pole-face losses and heating under certain conditions of load (see Art. 4).

Some consideration, however, should be given to the question of the sharing of the load between a number of water-driven alternators working in parallel. The subject is one that has received adequate treatment in various textbooks*; and it is here proposed to give only a *resumé* of the principal results as they apply to hydro-electric practice.

It was seen in Art. 3, p. 7, that the excitation which would produce the terminal pressure OC on open-circuit, would alternatively produce the stator current OH×OD/OG on short-circuit. Thus it might be considered that on short-circuit the exciting current actually produces the induced voltage OC, which is then absorbed in the passage of current through the stator winding; thus, virtually, the combined effect of resistance, leakage reactance, and true armature reaction is represented by a simple impedance. Further, since the stator resistance is negligible in comparison with the two other terms, it is usual to denote the ratio of open-circuit volts to short-circuit amperes corresponding to the same excitation as the *synchronous reactance* of the machine. If the magnetization curve were a straight line throughout, the synchronous reactance would be a constant quantity; but owing to the actual form of the curve, the equivalent reactance varies for different parts of the curve, and it is necessary to take a value appropriate to the region of working considered. Thus the term may be defined more logically as the variation of voltage accompanying a unit change of wattless stator current, the excitation remaining constant. Defined in this way, a value is readily found for the synchronous reactance at any point on the magnetization curve; but to obtain an indication of the performance of the machine over, say, its full working range, an average value may be taken, equal to the rise in volts when full wattless current is thrown off, divided by that current. Thus, referring again to fig. 3, if EF be extended until the line joining G and O is equal to OE′, then EG/OI is the average synchronous reactance over the range from zero to the load represented by the current OI.

Consider now the performance of a machine A, fig. 6 (*a*), which is to be paralleled with bus-bars on which a large number of other machines are working, so that the frequency and voltage of the station are fixed independently of the behaviour of the single machine considered. Let OE represent the fixed pressure of the bus-bars; then if the incoming unit be run up to exactly the frequency of the station, excited exactly to the voltage OE, and

* See, for example, Miles Walker, *The Specification and Design of Dynamo-electric Machinery*, 1915, p. 337, where also is given a useful list of textbooks, papers, and articles dealing with the parallel operation of alternators.

synchronized, it will carry no current whatever when connected in parallel. If now the excitation of the added machine be increased, and its induced voltage be represented by OE′, the pressure difference EE′, acting around the circuit formed between the machine A and all others in parallel therewith, will cause a *wattless* current OI to circulate; here EE′/OI is practically the synchronous reactance of the single generator A, that of all the remaining units in parallel being neglected. If, alternatively, with the original excitation, the driving torque of the added unit be increased, the rotor will be accelerated, and the terminal pressure will advance in phase relatively to OE. When a position such as OE′, fig. 6 (*c*), has been reached, the pressure difference EE′, acting in the inductive local circuit, will produce a current OI, now practically *in phase with* OE′, and therefore corresponding to an output of power from the generator considered. The rotor will thus continue running at the frequency of the bus-bars, and with such

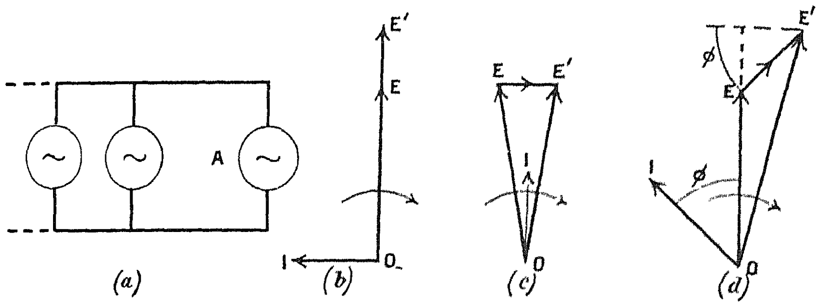


Fig. 6.—Variation of Load

(*a*) Diagram of circuit. (*b*) Pure wattless current. (*c*) Pure power current. (*d*) Normal load current.

an angle between OE and OE′ as to produce a load current equivalent to the driving power now supplied by the turbine. In actual working these two elementary conditions are combined, and the induced pressure OE′, in any particular machine, is related to the bus-bar pressure OE as shown in fig. 6 (*d*). Herein the excitation (difference in the lengths of the two pressure vectors) controls the wattless component of the current, while the useful driving power applied (angular displacement between the vectors) determines the power component of the current.

Consider now the effect of an increase of the *wattless* component of the total load on a station, in which a number of alternators are working in parallel. The division of the increment of wattless current between the several machines is determined by the fact that their terminal pressures must all remain identical; that is, that the drop in pressure must be the same for each generator. Hence, the extra current will be shared in inverse proportion to the synchronous reactances of the various machines; and in order that this may be also in the ratio of their rated capacities, the synchronous reactance of each machine should be inversely proportional to its rating. If it is required that the total wattless current be divided exactly proportionately over the entire range from zero to full load, it is

necessary that all the machines have magnetization curves of similar shapes, and that all have the same percentage regulation at normal load and power factor. This, however, is not practically necessary; for if the wattless current be suitably divided at the average working load by the adjustment of the excitation of the individual machines, and if all the machines have approximately equal synchronous impedances, approximately the same division of the wattless current will be maintained with considerable variations of load in either direction. Thus it is usually sufficient to ensure that a number of alternators which are to work in parallel have approximately the same percentage regulation at normal load; but a more useful criterion would be that all the machines give the same variation of terminal voltage for a change of load from, say, three-fourths to full load, at normal power factor.

Regarding the effect of a change in the *power* component of the total current, i.e. a change in the total kilowatt output of the station, the determining condition which comes into consideration is that, provided all the machines remain in synchronism, they must run at precisely equal speeds. It is necessary now, however, to distinguish between the instantaneous and the permanent sharing of a change of load. The immediate effect of an increase of load is a slight deceleration of the whole station, and the additional load will be so shared between the several units that the rate of fall of speed is the same for each; that is, each machine will carry a fraction of the increase of load proportional to its stored kinetic energy. The fly-wheel effect of each generating unit should therefore be in proportion to its rated output. The permanent division of the load, on the other hand, depends only upon the characteristics of the governors of the several turbines. The circumstances are exactly analogous to those of the sharing of wattless current as dependent upon the inherent regulation of the alternators. Since the actual fraction of the average total load which is carried by each unit can be suitably adjusted by individual regulation of the governors, the most logical requirement would be that each governor should give the same change of speed between, say, three-quarters and full load; but the more usual approximate specification is that the total variation of speed, corresponding to the movement of the governor from the " closed " to the " full-gate " position, should be the same for each set. With units of different governor and fly-wheel characteristics working in parallel, a change of load may at first be taken by one machine, or group of machines, to be finally transferred to another.

From the point of view of parallel operation it will be seen that coarse inherent regulation of both voltage and speed is advantageous, since it gives a more stable distribution of the wattless and power current respectively between the several units. With close regulation, a very slight dissimilarity in any one unit results in that machine taking considerably more than its due proportion of the load.

In the above discussion it has been assumed that the whole of the plant remains in synchronism. That this very necessary condition may not always be fulfilled, however, when units of different characteristics are working in

parallel, may be seen from a modification of the vector diagram shown in fig. 6 (*c*). The circulating current is here not entirely in phase with the terminal pressure, and thus only the projection of OI upon OE represents the true power delivered by the particular alternator considered. Now, as the angle EOE′ is increased (see fig. 7), the point E′ moves over a semicircle having O as centre and EO as radius; and since OI is always perpendicular to EE′ and proportional thereto, the point I moves over a semicircle described on OB as diameter, where OB = EA ÷ synchronous reactance, and is at right angles to EO. Hence, the maximum length of the projection of OI on to OE is equal to OB/2, and this condition occurs when the angle EOI is 45°, that is when OE′ is perpendicular to OE. If the angle EOE′ be increased beyond this point, although the actual circulating current continues to increase, the power delivered by the machine diminishes.

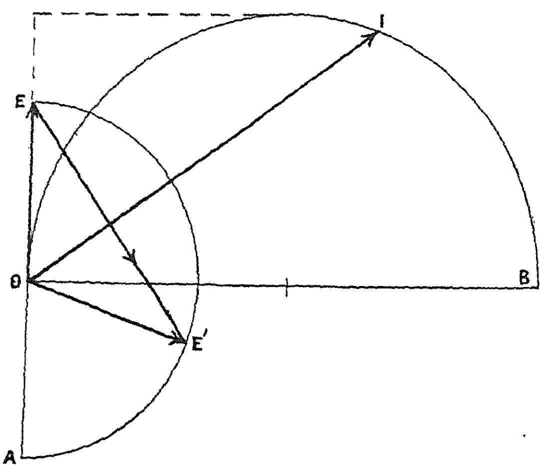


Fig. 7.—Maximum Power Output of Alternator

Thus, while it is not necessary that the fly-wheel effect of each generating set be strictly proportional to the output of the alternator, for only the distribution of the momentary variations of load is thereby affected, yet an approximate proportionality is desirable. For if one generating unit has a fly-wheel effect much greater than in proportion to its normal capacity, its maximum power output may be less than corresponds to the torque which would be derived from its stored energy with a sudden and large change of load, if the machine continued to run at the same speed as the remainder of the plant; the unit must consequently fall out of synchronism. For this reason the alternator of a "fly-wheel set" has to be designed to yield a maximum torque many times greater than that represented by its "equivalent" or time-average rating.

8. Wave Form.—For many important reasons the *sine wave* is recognized as the standard or ideal wave form of alternating pressures or currents in the generation of electrical power. Not only is this form more easily realized in the construction of alternators than would be any other particular wave shape, but appreciable departure therefrom generally gives rise to serious difficulties in operation, among which may be mentioned: permanent circulating currents in the parallel working of machines of different design; static and other troubles with an earthed neutral point; "crawling" of induction motors, or bad commutation of rotary converters, working on

the system; excessive charging currents, or possible resonance in transmission lines; and interference with neighbouring telephone circuits. In dealing with an irregular or non-sinusoidal wave form, it is convenient to resolve it into a *fundamental* (or pure sine wave) component, having the frequency of the whole wave, and a number of *harmonics*, each of which is again a sine wave having a frequency which is an integral multiple (in nearly all cases an *odd* multiple) of the fundamental frequency. The badness of an irregular wave is then indicated precisely by the magnitude of the harmonic terms which it is found to contain, and undesirable results of various kinds can, as a rule, be attributed to harmonics of particular orders or classes.

The wave form of the terminal pressure, under any condition of load, may here be taken as very nearly the same as that of the induced pressure; and the latter depends solely upon (i) the distribution (over the pole-pitch) of the magnetic field in the air-gap, and (ii) the arrangement of the active conductors of the stator winding. With a purely sinusoidal flux distribution, the induced-pressure wave will be a true sine wave whatever the type of winding employed. With an irregular field-form, the pressure wave will always be *more nearly* sinusoidal than the wave of the flux distribution, the harmonics being reduced, relatively to the fundamental, to a degree which depends upon the disposition of the stator conductors. Now, while it would be possible, by the special shaping of the poles, to produce a perfect sine wave of flux distribution on no-load, the effect of armature reaction is such that this form cannot be maintained, in a salient-pole machine, under the working condition of load. Nevertheless, a well-shaped pole tends to minimize the distortion of the field on load. Thus, while every endeavour should be made to produce an approximately sinusoidal air-gap field on open-circuit, this alone would be insufficient; and the realization of a satisfactory pressure wave-shape under load necessarily depends also upon the properties of the stator winding.

By far the most serious, and probably the largest, harmonic in the wave of flux distribution is the *third*. With an air-gap of uniform radial width over the whole surface of the pole, the field-form might be represented, to a first approximation, by a series of positive and negative rectangles having the same peripheral width as the pole face, as shown in fig. 8, curve *a*; and with this form it would be possible to eliminate entirely any one harmonic, on no-load, by a suitable choice of the width of the pole. For example, with a pole-width equal to two-thirds of the total pole-pitch, there would be no third harmonic; while with a pole covering four-fifths of the pole-pitch, there would be no fifth harmonic. However, with a uniform air-gap over the pole, "fringing" or the spreading of the flux at the tips of the poles (so as to enter the stator in the interpolar region) considerably modifies the simple rectangle, and gives actually a form similar to that indicated by the curve *b*. The effect is that, even with a "two-thirds" pole, a third harmonic remains, which can only be eliminated by further reducing the width of the pole; and this would involve so great a loss of output from a machine of given size as to render it inadmissible in practice. The fifth harmonic, on the

other hand, might be eliminated by somewhat increasing the width of the pole—a device in which there is also some economic advantage; but in any case the fifth is very greatly reduced by the armature winding, while the third is further increased by widening the pole; and the best compromise is usually found with a pole-width only slightly exceeding two-thirds of the pole-pitch.

It is, however, possible to reduce both the third and fifth harmonics simultaneously by so forming the pole face that the gap at the tips is about twice as wide as over the centre of the pole. With poles or pole-shoes built up of stampings (see Art. 6, p. 74), it is a simple matter to obtain any

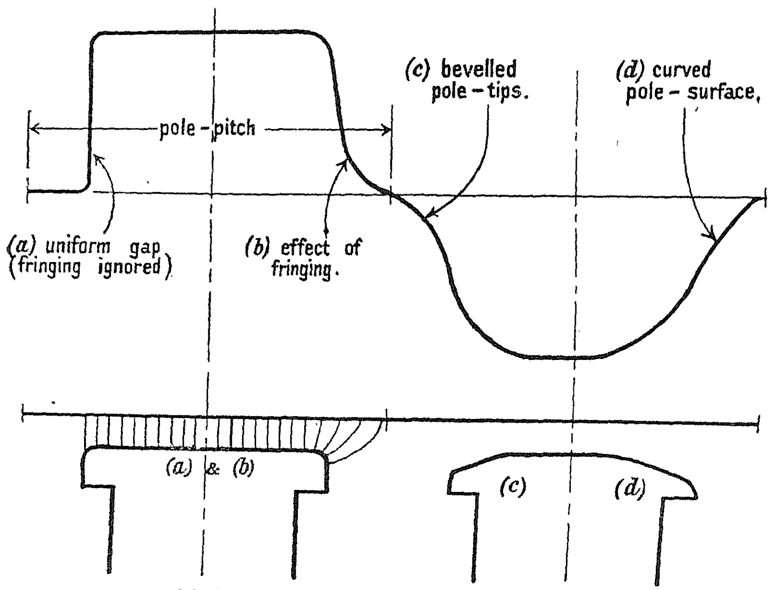


Fig. 8.—Field Wave Form of Salient-pole Alternator

desired profile, resulting in a perfectly smooth flux density wave free from objectionable harmonics. Where the poles are of cast steel, or are machined from mild-steel billets, it is usually only feasible to use a single flat bevel, or a simple rounded corner (curve *c*); yet even this approximation may greatly improve the wave form as regards the lower harmonics, and is, moreover, especially valuable where there would probably be difficulties due to tooth ripples (p. 28). An alternative device, applicable to solid poles, and giving an excellent flux wave form (curve *d*), is to machine the pole surfaces to a considerably smaller radius (depending upon the number of poles) than that of the stator bore; but this operation can only be carried out economically with certain proportions of the pole, and involves also some loss of output.

Now the presence of harmonics of the lower orders in the wave form of the terminal pressure, under any condition of load, may occasion serious difficulties. This is the case, in particular, with the third harmonic in a

three-phase system; for, owing to the coincidence of its order with the number of phases, this term reaches its maximum value simultaneously in all the phases, and so gives rise to peculiar phenomena. For example, if a three-phase generator be connected in "mesh" or "delta" (i.e. the start of each phase joined to the finish of the next, so as to form a closed circuit), although the sum of the three fundamental pressures is zero at every instant, any third harmonics are directly additive, and produce a circulating current within the winding. Such a current may be very large, and result in serious additional losses and heating, both in the stator winding and in the pole surfaces. With this method of connection, however, there can remain no third harmonic in the line voltage, for this term is exactly neutralized by the leakage reactance and armature reaction set up by the circulating current. On the other hand, when the winding is connected in "star" or "Y" (i.e. the starting-points of all three phases joined together to form a "neutral point"), the potential of the neutral point relatively to earth will pulsate by the amount of the third harmonic in one phase, and with the corresponding triple frequency. Again the harmonic is entirely eliminated from the line pressure, which is now at any instant the difference between two-phase pressures. Alternatively, if the neutral point is earthed, the third harmonic pressure is superposed upon the potential of each line above earth; the stress upon the insulation is generally increased,* while a large triple-frequency charging current in the transmission line, or in some cases resonance effects, may result. Further, when several generators with earthed neutrals are connected to the same bus-bars, unless the triple harmonics in all the machines are exactly identical both in magnitude and phase, circulating currents between the several machines occur, completing their circuits through the common neutral connection, and attended by extra losses as in a delta-connected generator. Similarly, if any other machinery with earthed neutral is working on the system external to the power house, earth currents are set up by the differences between the triple-harmonic voltages of the various machines; while if the neutral points of the external plant are insulated from earth, these points will pulsate with a triple-frequency voltage, which in high-tension machinery may constitute a serious danger from accidental contact.

The question of grounding or insulating the neutral point of the generating plant, apart from the effects of triple harmonics, may conveniently be dealt with briefly at this point. The choice between the two methods involves many considerations of detail, but is mainly dependent upon whether continuity of supply, or the prevention of abnormal pressures, is the more important. If the neutral is left ungrounded, an accidental earth on one line will not necessarily interrupt the service, but will raise the maximum potential of the generator (or step-up transformers) to the full line voltage above earth. When step-up auto-transformers are employed, the conditions are still more severe; for the low-tension generator winding may then be raised to the full transmission line voltage above earth. A dead-earthed neutral, on the other

* This depends upon the phase of the third harmonic relative to the fundamental, which, however, is nearly always such as to increase the maximum or peak value of the line pressure.

hand, restricts the maximum potential of the winding to the phase pressure; but an earth on any line now constitutes a short-circuit on one phase. By connecting the neutral point to ground through a resistance, the initial rush of current, in the event of an earth on one line, can be limited to only a sufficient value to operate the protective gear, and thus mechanical damage to the windings may be prevented; but with this arrangement the abnormal voltage is not avoided, and the machines must be adequately insulated to withstand the full line pressure to earth.

The fifth, seventh, and higher harmonics, except those which are multiples of three in a three-phase system, have exactly the same characteristics as the fundamental. They appear in the interlinked line pressure with the same percentage values that they have in the phase pressure, although the signs of certain terms are reversed and thereby the appearance of the wave form radically altered. These harmonics do not cause circulating currents in delta-connected windings, nor in the common neutral lead of star-connected generators. In two-phase machines, all odd harmonics behave in the same manner as the fundamental (ignoring changes of sign); that is, the multiples of three here exhibit no special properties. A seventh harmonic in the line pressure may interfere with the starting of induction motors by producing a torque in the reverse direction; but unless the seventh harmonic is abnormally large, trouble of this kind is rarely experienced except with motors having a low starting-torque (such as the "squirrel-cage" type) when required to start under load. Both the fifth and seventh terms may result in bad commutation in rotary converters; for the armature reaction set up by them causes a rapid pulsation in the strength of the interpole field. The possibility of excessive capacity currents in the transmission lines, or of resonance effects, is present with harmonics of *any* order.

The property of the armature winding in reducing the relative effective values of harmonics remaining in the flux-density wave, depends upon the product of the *distribution factor* and the *coil-span factor*, which were introduced on p. 6 in their application to the fundamental. In the case of the harmonic of the nth order (i.e. having n times the frequency of the whole wave), the expressions for these two factors become

$$\text{distribution factor} = \frac{\sin ns\pi}{ns\pi};$$

$$\text{coil-span factor} = \sin n\frac{\pi}{2}\left(\frac{\text{slot pitches spanned by mean coil}}{\text{slot pitches per pole}}\right).$$

Now it will readily be seen that the possible values of s, the fraction of the double pole-pitch which is occupied by one phase, are strictly limited—in polyphase machines—by practical considerations of the arrangement of the winding. In a three-phase winding, s may be either one-sixth or one-third, the latter, however, being practicable only with a two-layer winding (see Art. 4, p. 66); while in a two-phase winding, s rarely differs from one-fourth. In a single-phase machine this restriction is absent, but for various practical

reasons s is then usually about one-third. The numerical values of the distribution factor for these common values of s, and for a series of the lower harmonics, are as follows:

DISTRIBUTION FACTOR

Phase-spread. / Double pole-pitch.		$s = \frac{1}{6}$.	$s = \frac{1}{4}$.	$s = \frac{1}{3}$.
Order of harmonic	$n = 1$	0·955	0·900	0·827
	$n = 3$	0·637	0·300	0
	$n = 5$	0·191	—·180	—·165
	$n = 7$	—·136	—·129	0·118
	$n = 9$	—·212	0·100	0·092

The coil-span, in the majority of windings, is equal to the pole-pitch, this value alone being practically convenient with single-layer windings. Where, however, it is possible to vary the coil-span, as in two-layer windings, there is often much advantage in making the span of the coil somewhat less than the full pole-pitch, giving what is known as a "short-pitch" or "chorded" winding. The following table gives the numerical values of the coil-span factor for simple values of the ratio of coil-span to pole-pitch, and for various harmonics; intermediate values may easily be estimated.

COIL-SPAN FACTOR

Coil-span. / Pole-pitch.		1·0	0·9.	0·8.	0·75.	0·7.	0·67.	0·6.	0·5.
Order of harmonic	$n = 1$	1·000	0·988	0·951	0·924	0·891	0·866	0·809	0·707
	$n = 3$	1·000	0·891	—·583	—·383	—·156	0	0·309	0·707
	$n = 5$	1·000	0·707	0	—·383	—·707	—·866	—1·000	—·707
	$n = 7$	1·000	0·454	0·588	0·924	0·988	0·866	0·309	—·707
	$n = 9$	1·000	0·156	—·951	—·924	—·454	0	0·809	0·707

It will be seen that, by the distribution of the winding alone, the third harmonic is reduced to two-thirds of its original value relatively to the fundamental, in the standard three-phase winding (s = one-sixth); and to one-third in the standard two-phase winding; but, further, that this term is reduced to *zero* in a three-phase winding spread over twice the usual angle. Alternatively, in any winding, the triple-frequency terms can be entirely eliminated in virtue of the coil-span factor, by using a coil-span of only *two-thirds* of the pole-pitch. At the same time, however, with the wide phase-spread (s = one-third) or the two-thirds coil-span, the fundamental—and the effective output of the machine—is reduced to 87 per cent of its value for the narrow phase-spread (s = one-sixth) and full-pitch coils. For this reason neither the wide phase-spread nor so narrow a coil-span as two-thirds is commonly employed in alternator windings, unless it is essential

that there be no triple-frequency term whatever in the phase pressure under any conditions of load; and, in general, reliance is placed upon obtaining a good field-form for the sufficient reduction of this harmonic.

In each of the three types of winding referred to, the fifth harmonic is reduced to only one-fifth of the percentage value which it has in the wave of flux distribution, in some cases with a change of sign. Owing to this fortunate circumstance, it is unnecessary to reduce this harmonic in the field-form to a particularly small value, which indeed would be difficult to accomplish with certainty even for the open-circuit condition. By the use of a coil-span of exactly *four-fifths* of the pole-pitch, any remaining fifth harmonic might be removed, should exceptional conditions of operation (such as perfect resonance) occasionally demand this. However, while the phase-spread is limited to one or two definite values, any intermediate value of the coil-span between two-thirds and full pitch is easily obtained; and since some degree of "chording" is an advantage as regards the losses on load, a coil-span of 75 to 80 per cent is very commonly adopted. Incidentally the fifth harmonic is thereby almost entirely eliminated and the third very effectively reduced; at the same time the loss of output—about 6 per cent—is not serious.

The expression given above for the distribution factor strictly refers to a *uniformly distributed* winding, or one in which there is a very large number of slots per pole. In applying this formula to a practical winding, in which there is a comparatively small number of slots, no important error is made in the case of the lower harmonics, such as are tabulated above; but when dealing with terms of much higher orders it is essential to use the complete formula:

$$\text{distribution factor} = \frac{\sin ns\pi}{q\sin(ns\pi/q)}.$$

wherein q denotes the number of slots per pole which are occupied by one phase. The factor for a uniformly distributed winding continually diminishes as the order of the harmonic in question is increased; but it will be found that the latter expression—for a finite number of slots—increases and decreases periodically. In particular, for terms of the orders $q/s \pm 1$, that is, for $n =$ (slots per pole-pair) ± 1, the distribution factor attains the same numerical value as for the fundamental. Harmonics of these particular orders, if present in the air-gap field, appear in the terminal pressure waves with their full percentage values. Such terms are usually known as *spacing ripples*, since the effect is attributable to the regular spacing of the stator conductors.

If the stator face were quite smooth, the terms of these higher orders in the field form would be insignificantly small. When, however, the stator face is broken up into alternate slot openings and teeth, as is universal practice, the wave of flux density is serrated, and precisely those harmonics are introduced which are not diminished by the distribution factor. The much larger and highly important harmonics which thus appear in the pressure waves, are known as *tooth-* or *slot-ripples*, from their origin in the local variations of flux density, caused by teeth- or slot-openings.

With a very small number of slots per pole, the tooth-ripple may be of low enough frequency to give rise to troubles from capacity currents or resonance. For example, with six slots per pole in a three-phase machine, i.e. two coils per group, the tooth-ripple will consist of the eleventh and thirteenth harmonics, and these can be large enough to cause serious difficulties. With larger numbers of slots per pole, the ripple may interfere with the working of telephone systems in the vicinity of the lines, either by electrostatic or electromagnetic induction; and in this respect a very small harmonic may have disastrous effects. It is desirable in all cases, therefore, to ensure that the tooth-ripple will not be large; and where the conditions of operation indicate that either of the above difficulties is probable, special precautions must be taken to reduce these terms to the smallest practicable limits.

For this purpose various means are available. One of the most usual methods is to employ semi-closed or totally-closed stator slots. Totally-closed slots increase the leakage reactance of the winding under normal load conditions, without affording additional protection in case of sudden short-circuit; they are used only in exceptional circumstances. Provided that the slot opening is less than one-half of the radial width of the air-gap, the flux density remains very nearly uniform over the slot-pitch, and the tooth-ripples are usually unimportant. There are, however, practical disadvantages in the use of semi-closed slots. The coils must be formed in position, at least at one end, and there must be appreciable slackness in the slots in order that the coil may be pushed through from one end. The initial cost of winding, and the difficulty of replacing a damaged coil, are thus greatly increased. With plain open slots, the tooth-ripple may be reduced by using a large number of narrow slots per pole rather than a small number of wider slots; but at the same time the stiffness of the coils and their ability to withstand the mechanical stress of short-circuit is impaired, the initial cost of winding is increased, and—particularly in high-tension machines—valuable space is wasted in numerous thicknesses of the main insulation. From these practical considerations, it becomes almost essential to use a comparatively small number of open slots, having a width of about twice the radial air-gap; and, in the absence of additional precautions, this would inevitably lead to excessive tooth-ripples.

In large machines, open slots may be closed by magnetic wedges, built up of thin sheet-iron stampings riveted together in packets about an inch wide, and perforated to reduce the leakage and loss in them, and to provide for ventilation. When the simpler non-magnetic wedges must be used, as in ordinary practice, a limited number of slots can be arranged to yield the effect of a much larger number, as regards wave form, by using a fractional number of slots per pole. This can be done in either of two ways. In one method, a standard single-layer winding is used, but one, two, or three additional empty slots are inserted. With either one or two extra slots in a three-phase machine, the tooth-ripples are greatly reduced, but the three phases are slightly unsymmetrical, and generally more so than is permissible

In machines cooled by the natural circulation of air, or by an internal fan mounted on the rotor, these two items are merged in a single loss associated with the ventilation.

The total mechanical losses may be measured by driving the alternator at normal speed and unexcited, by means of an electric motor, the losses in which are known.* If there is a separate blower, the power supplied to it is readily measured electrically, and is added to the driving power required by the generator itself. When a calibrated driving motor of sufficient power is not available, the various component losses must be examined separately.

For the bearing losses there are no reliable means of direct measurement, those methods which depend upon an observation of the weight and temperature rise of the lubricating oil being liable to serious error on account of the heat conducted to the bedplate or along the shaft. The mechanical friction must therefore be estimated by a comparison with other cases for which direct experimental data are available.

The ventilation losses occurring within the machine itself, when of the *enclosed* type (in which the air enters by a duct and is discharged at a chimney), may be measured by the "air-heating" method (p. 40), when the alternator is driven by the turbine at normal speed and unexcited. This method is especially valuable when the stator core has to be built in the power house, as in the case of very large machines, or where there are exceptional difficulties in transport. The loss thus measured is the sum of fan power and true windage. When an external blower is used, however, it is necessary to observe the temperature rise of the cooling air between the points at which it enters the blower and is discharged from the stator chimney, in order that the losses within the fan may be included in the measured total. A further allowance, amounting to possibly 10 per cent of the fan power, has to be added to cover losses in the fan motor.

With *open*-type machines, in the absence of a direct measurement by means of a driving motor, both the bearing friction and the ventilation loss must be estimated.

As an approximate indication of the losses to be anticipated, the combined friction, windage, and fan losses in medium and large alternators of the enclosed waterwheel type, self-ventilated by fans fitted to the rotor, may be taken as 0·6 per cent of the k.v.a. rating of the machine for normal temperatures.† In open-type machines, without fans, the percentage friction and windage loss is again about 0·6, on account of the reduced output of such machines; and where fan blades are fitted this

* On account of simplicity of speed adjustment, a direct-current motor is preferable for this purpose. The armature copper and brush losses are usually unimportant. If the supply voltage can be varied, the excitation of the motor may be kept constant; the core loss then remains practically constant, and the sum of bearing friction and core loss can be measured by the input to the motor when running light, disconnected from the alternator. If the supply pressure is fixed, allowance must be made for the effect upon the core loss of variations in field-current required to maintain a constant speed.

† In generators working at temperatures below standard the mechanical losses are, of course, increased.

figure may be raised to 0·8 or even 1·0 per cent. In generators of the enclosed type to which air is supplied by an external motor-driven blower, it is usually essential also to provide fan blades on the rotor to direct the air with a sufficient velocity over the cooling surfaces. Such fans may be smaller than where the flow of air depends entirely upon them; but a total driving power of 0·4 to 0·5 per cent of the k.v.a. output should still be allowed. In addition the driving power required by the blower motor, supplying approximately 2·5 c. ft. of air per minute per k.v.a., at a net pressure of 2 in. water-gauge, will be 0·5 to 0·6 per cent.

3. Open-circuit Losses.—When an alternator is excited while running on open-circuit, in addition to the mechanical losses, power is absorbed in excitation and iron losses. The former, which is the copper loss of the field winding, is supplied electrically, and is readily calculated from the square of the exciting current (taken from the open-circuit curve) and the resistance of the field winding, with an allowance for its increase with temperature; or during a test, the excitation loss is given directly by the product of the measured exciting current and the measured pressure between the slip-rings. The remaining loss, which is supplied mechanically to the alternator shaft, represents principally the power absorbed in hysteresis and eddy currents accompanying the reversal and variation of flux in the stator laminations; but this true iron loss is supplemented by eddy-current losses occurring in both iron and copper in other parts of the machine.

The hysteresis loss is proportional to the weight of steel, to the frequency, and approximately to the 1·6th power of the flux-density; but its actual magnitude depends upon the magnetic quality of the steel. In general, the "softer" the steel (or the lower its carbon content) the smaller is the hysteresis loss. The eddy current loss within the laminations is proportional to the weight of steel, to the square of the frequency, the square of the flux density, and the square of the thickness of the plates; and depends also upon the electrical resistivity of the steel. The higher the resistivity the smaller are the eddy currents.

Two grades of sheet steel are in common use. The cheaper or "ordinary" quality is used, as a rule, in waterwheel alternators of small and medium outputs. In large machines, especially with a small number of poles and running at a high speed, the heat due to losses in the core has to traverse a considerable distance to the cooling surfaces; and it is then often more economical to reduce the losses by using a higher grade of steel rather than by increasing the amount of active material. For machines of this class, special steels, known under various commercial names, such as Extra Lohys, Loloss, and Special Dynamo Steel, are in use; these materials have very small hysteresis loss. Alloy steels are also available, which have particularly high electrical resistivity and therefore very small eddy current losses. These materials, however, are much more expensive than ordinary iron, are more difficult to punch accurately and without burrs, owing to excessive wear of the press tools, and are brittle; they are very rarely used in alternator cores, except perhaps at very high frequencies as an alternative to much fine

lamination with ordinary steels. The average total loss, including both hysteresis and eddy currents, in the three main classes of core steel, at a flux density of 10,000 c.g.s. lines per square centimetre, and at a frequency of 50 cycles per second, is as follows:

Ordinary steel	1·2 to 1·5 watts per pound.
Special steel	0·9 to 1·2 watts per pound.
Alloy steel (Stalloy)	0·7 to 0·8 watts per pound.

These figures represent the loss as measured with the "Epstein Square" in carefully prepared sample strips.

Whatever material is used, however, the iron losses occurring in a machine are always largely in excess of those calculated from the results of laboratory tests on samples of the steel, at the same flux densities and frequencies. This is due, to a small extent, to non-uniform distribution of the flux over the cross section of the magnetic circuit, owing to the circular form of the stator core; but principally to the existence of many other paths in which eddy currents may be formed, other than those within the sections of the individual laminæ. Wherever there is a punched edge, the press tool inevitably forms a small burr on the stamping, which it is essential to remove either by filing or grinding; but with large stampings, even when every care is exercised, many burrs always remain, and may form electrical circuits between adjacent plates. The more complex the form of the stamping the greater is the liability to additional losses due to burrs; and axial holes in particular materially increase the loss both on account of burrs and irregularity of flux distribution. The loss due to occasional burrs remaining may often be practically eliminated by inserting a stamping of thick paper at about every half-inch of the core length. Filing or drifting of the slots to remove irregularities after the core is built, also produces extra losses and greater temperature rise in a region where its effect is most serious; hence the importance of accurate punching, and close fitting of the stampings in the stator frame. In some types of stator construction the plates are clamped together by axial bolts passing through the core. Such bolts must be thoroughly insulated throughout their length, and under the nuts or washers (Art. 3, Chap. IV). The electrical connection between adjacent laminæ occurring formed by their common contact with the frame casting does not form an eddy current path when the flux density in the core is low, since no flux then passes through the electrical circuits so formed; but at higher core densities there is a leakage of flux into the cast iron, which causes eddy currents to pass between the core plates and the axial ribs or keys of the frame. As the flux density is raised, a point is reached beyond which the loss increases very rapidly; and damage may be done by local heating at the contacts between core and frame. Such trouble is most often found in 25-cycle machines, since from other points of view high core-densities are then permissible.

Apart from the above-described extra losses which arise from imperfect construction, certain others are inherent in the normal construction of

alternators. The laminations are necessarily clamped between thick end-plates, either of cast iron or steel; and in these large eddy currents are set up, especially at high core-densities. Likewise it is essential, from mechanical considerations, to use thicker laminæ, never less than ·035 in., on either side of each radial vent; and a further loss occurs at the vents due to flux entering the plates normally to their surfaces, and consequently setting up eddies in the plane of the laminæ.

The losses already described occur in the stator iron; in addition there may be losses (on open-circuit) in the stator conductors and in the pole-faces of the field magnet. Owing to the reluctance of the teeth a portion of the flux passes radially through the stator slots, and induces eddy currents in the copper conductors therein. This loss increases very rapidly with the saturation of the teeth and with the width of the copper; and, unless the tooth density is exceptionally low, the width of the copper strip must not exceed about 0·6 in. for a frequency of 50 cycles per second. At higher tooth-densities, or where a greater total width of copper is required, the strip must be divided into two or more separately insulated wires placed side by side in the slot. In a delta- or mesh-connected stator winding there may also be copper loss due to a high-frequency circulating current set up by a third harmonic in the field wave-form (see p. 23). In machines of modern design such currents should be negligibly small.

Losses in the pole-face are due to eddy currents set up by the rapid variations of flux occurring as the poles move past the stator teeth. These losses vary between wide limits. With semi-closed slots and laminated poles, the loss is negligible. With solid poles the loss is small, provided that the slot opening is not greater than two-thirds of the radial width of the air-gap; but beyond this limit the pole-face loss increases very rapidly. With laminated poles the loss does not become important until the slot opening reaches some three or four times the width of the air-gap. Excessive pole-face losses are particularly to be avoided, since, apart from reduction of the efficiency, they increase the temperature rise of both field and stator windings.

The total losses in cores built up from stampings of "special steel" are some 20 per cent less than when "ordinary" quality iron is used. Most of the extra losses are small at low densities, but increase very rapidly beyond the point at which magnetic saturation commences.

The open-circuit losses may be measured by means of a calibrated driving motor, as in the case of the mechanical losses (Art. 2), or by the air-heating method (p. 40), when the alternator is running excited at normal speed.

4. Short-circuit Losses.—The losses occurring on short-circuit comprise the mechanical losses described in Art. 2, the excitation loss (which may be found from the short-circuit characteristic), a small stator iron loss, copper losses in the stator winding, and a number of widely variable losses distributed over the iron parts of the machine, and generally grouped together under the title of "stray loss". The stator core loss is due to the small main flux which is necessary to neutralize the effect of the stator leakage fluxes; this may be taken from the curve of open-circuit losses at

the voltage corresponding to the reactive pressure drop in the stator winding (p. 8).

The stator copper loss per phase includes the common Joule's loss as given by the square of the stator current per phase, multiplied by the simple ohmic resistance per phase of the winding (as measured by direct current); and also power absorbed by eddy currents which are induced in the conductors when carrying an alternating current. Eddy currents in the stator winding have an important influence upon the temperature rise, and require further examination.

The current-carrying conductors produce an alternating flux, which passes transversely across the stator slots and induces a longitudinal eddy current in each strip of copper lying in the slot. The direction of flow of the extra current, at the side of the strip nearer the slot opening, is the same as that of the main current, and at the side of the strip remote from the slot opening is in the opposite direction; the result is that the total current is non-uniformly distributed over the depth of the copper. The eddy currents are clearly proportional to the transverse flux, that is, to the main current; consequently the power absorbed by them, in any particular case, may be taken into account simply by an increase in the *effective resistance* of the winding.

Where there are a number of separate strips of copper in the slot, each carrying the same current, the transverse field strength and the eddy-current factor increase rapidly in passing from the strip nearest to the bottom of the slot to the one nearest to the top or slot-opening. The multiplying factor for the mth strip (counting from the bottom of the slot) is given by*

$$K_m = \left[\frac{4}{45} + \frac{m}{3}(m-1)\right]d^4. \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $d = \frac{1}{3}$ (depth of strip in inches) $\times \sqrt{}$(frequency) $\times\ \alpha$, and $\alpha =$ width of copper/width of slot.

This increase applies only to that length of the conductor which is embedded in the core, and in which alone these individual eddy-currents occur. It will be seen that K_m increases very rapidly with the depth or thickness of the strips, so that beyond a certain critical value any further increase in thickness results in a greater total loss in the copper. The transverse width of the strip is limited by the necessary width of the teeth; and a definite limit is thus set to the current-carrying capacity of each strip, the actual limit depending upon the total number of strips per slot, each carrying the same current. When larger currents have to be dealt with (as in low-voltage machines even of moderate output), it therefore becomes necessary to form the complete conductor of a number of separate strips connected in parallel.

However, for the same reasons that eddy currents are produced in the individual strips, circulating currents also flow between the several strips connected in parallel, passing through their common junction. The directions of the circulating currents are such that the larger proportion of the

* H. W. Taylor, *Journal, I. E. E.*, Vol. 58, p. 279. See also A. B. Field, *Transactions, Am. I. E. E.*, Vol. 24, p. 761.

resultant or main current passes through the strip nearest the slot opening. If the several strips or laminæ are simply joined together near the ends of each slot, the resultant distribution of current is practically the same as would obtain in a solid bar of the same total depth, and no advantage in respect of eddy-current losses is obtained from the lamination. On the other hand, if the several strips be transposed, either by special twisting within the slots (see Art. 4, Chap. IV), or by keeping the strips entirely separate throughout the winding and making the necessary cross-overs in the end connections, so that each strip occupies every position in the complete conductor over an equal length of the winding, the reactance of every path is the same, and there are no circulating currents. Only the eddy currents in the individual strips then remain.

Complete transposition, however, is rarely essential; and since a slight dissimilarity between the several paths in parallel often allows of a much simpler mechanical arrangement of the winding, such a scheme is very commonly adopted. In these cases the total loss is approximately equal to the sum of the loss due to the eddy currents in the individual strips (calculated from equation (1) as for a number of conductors in series), and the loss which would occur in the complete conductor if *very finely* laminated, and with the laminæ transposed according to the same system as the actual thick strips. The latter part of the loss also may be obtained from equation (1), if the factor a be multiplied by the fraction

$$\frac{\text{net depth of copper} \times \text{length of conductor between joints*}}{\text{gross depth of conductor} \times \text{length of core}}$$

and a fictitious depth of conductor be taken, depending upon the system of transposition.† For example, one of the simplest forms of partial transposition, and one which is often sufficient, is obtained in the ordinary lap-wound coil (Art. 4, Chap. IV), in which the separately-insulated laminæ are continued from one layer to the other without any special transposition. In this case a is multipled by half mean-turn/length of core, and the depth of copper is taken as *one-half* the gross depth of the complete conductor. The loss so obtained from equation (1), for the circulating currents in a finely laminated conductor, is added to the losses in the individual strips of the actual winding.

The factor for the loss due to circulating currents applies to the whole length of the winding between the joints. Such extra currents—if excessive—are particularly detrimental, since they pass through the end connections of the winding, which are more difficult to insulate with heat-resisting material than are the embedded portions of the coils. While, therefore, a local eddy-current loss of over 100 per cent in the top strip may give no trouble, the circulating current loss should generally not exceed 10 or 15 per cent.

The difference between the total loss found on short-circuit and the

* Or half the length of the mean turn, if less than the distance between the joints.

† See A. B. Field, loc. cit., p. 770.

sum of the components enumerated above is known as the "stray loss". The principal part of this additional loss is produced by the magnetic field of the armature winding, and occurs in all adjacent iron parts of both stator and rotor. The magnetomotive force of both the end connections and the embedded portion of a polyphase winding, when carrying a balanced load, consists of a fundamental component which revolves in the same direction and with the same speed as the rotor, and a series of harmonic terms which move with fractional speeds and in either direction. The fundamental term of the magnetic field of the end connections, having motion relatively to the stationary core end-plates, coil supports, clamping bolts, and the cast-iron guards enclosing the winding, produce considerable eddy currents and losses in these parts. The embedded portion of the stator winding produces no appreciable loss in virtue of its fundamental term, since there is no stationary solid iron in its vicinity; but the harmonic components, moving with nearly synchronous speed relatively to the rotor, may produce large eddy currents losses in the pole-faces. With laminated poles or pole-shoes, the loss on this account (in a polyphase machine supplying a *balanced* load) is hardly appreciable. When the pole-face is solid, however, the loss is greatly increased; and, although it still does not become a serious item in a three-phase machine, it may be important in a two-phase machine, owing to the presence of a large third harmonic (p. 23). With an *unbalanced* load there appears also a fundamental component of magnetomotive force moving in the opposite direction to the rotor, and therefore producing large pole-face losses, appreciable even with laminated poles. In the limiting case of the *single-phase* machine, where the two fundamental components are equal, the loss, even in a laminated pole, would be prohibitive; and it is then necessary to provide a heavy damping winding. Currents are induced in the damping winding which approximately neutralize all components of the stator field which have motion relatively to the poles; and, owing to the low resistance of the damper windings, these currents produce only a moderate loss. A damping winding in laminated poles is also desirable in two- or three-phase machines intended to work on unbalanced loads. The total amount of the stray loss increases rapidly with the total number of ampere conductors per pole in the stator winding, and with the mass of iron present; it is, therefore, much more important in large machines than in small machines, and greater with a small number of poles than with a large number. In very large high-speed machines, stray losses may amount to about two-thirds of the total loss in short-circuit.

The total short-circuit losses may be measured either by means of a driving motor or by the air-heating method.

5. Losses on Load.—Under normal load conditions the losses comprise the mechanical friction and ventilation loss (Art. 2), the excitation loss calculated from the load excitation (Art. 5, p. 10), the stator iron loss, stator copper loss, and stray losses.

The stator iron or core loss is greater than that measured at normal voltage on open-circuit, for two reasons. In the first place, the total induced

pressure on load is greater than the terminal voltage, on account of the leakage impedance drop in the stator winding; this increase may easily be calculated (Art. 5, p. 10), and on full load may amount to some 20 per cent of the loss on open-circuit. Further, the effect of the armature reaction is to distort the shape of the flux-density wave in the air-gap; so that, for the same induced pressure (i.e. approximately for the same total flux), the maximum flux density is considerably increased. The loss in the stator teeth depends upon this maximum density, and may therefore be much greater on load than on open-circuit with the same total flux. The importance of the effect upon the total iron loss, of course, depends upon the relative magnitudes of the losses in the teeth and in the remainder of the core behind the teeth, and therefore varies widely between different machines; but, as a general indication, the total core loss may often be increased by a further 20 per cent from this cause.

The stator copper loss, including the increase due to eddy currents and circulating currents, may be estimated as for the short-circuit condition. Allowance must also be made for the increase of resistance with the temperature rise of the winding, which on full load may amount to some 15 or 20 per cent; but it should be noticed that the eddy-current losses are somewhat reduced by increase of temperature. The stray losses on load are smaller than on short-circuit, but little data is available as to the exact relationship; as an approximate rule it may be assumed that about two-thirds of the short-circuit stray loss is present under normal working conditions.

The *efficiency* of a generator may be defined as the ratio of output to (output + losses); but in its numerical calculation it is more accurate to use the form:

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{output} + \text{losses}}.$$

In practice it is necessary to distinguish between the "true" efficiency and the "conventional" efficiency of a machine. In the *true* efficiency every loss associated with the operation of the generator is taken into account; so that the total losses are simply the difference between electrical power output of the machine and the mechanical power supplied to the shaft by the turbine, together with any power supplied to the machine electrically (as in excitation), or absorbed in auxiliary apparatus (such as a fan motor, rheostats, &c.). It is usually desirable, however, to be able to prove the compliance of a generator with its specification, in respect of losses, by means of tests which can be carried out at the makers' works, where the power supply available will generally be much less than the full capacity of the machine under test. A *conventional* definition of efficiency, based upon a summation of the losses measured separately under no-load conditions, is then adopted. For this purpose the rules followed in British practice differ somewhat from those used in America. In either method is included the mechanical friction and windage losses, the excitation loss based upon the calculated exciting

current for normal load conditions and the hot resistance of the field winding, and the loss in a series rheostat when this is employed, or in the exciter itself if each generator has a separate exciter. In the British method the core loss is taken as that measured on open-circuit at normal terminal pressure, while the stator copper loss is taken as the simple ohmic loss, with allowance for the temperature rise of the winding, all extra losses being usually neglected. The resulting efficiency is necessarily lower than the true efficiency, the difference varying as a rule between $\frac{1}{2}$ per cent in small machines to 1 per cent in large machines. In the American rules the core loss is taken as that measured on open-circuit at a pressure equal to the calculated induced voltage on load, and the sum of stator copper loss and stray losses is taken as the total loss measured on short-circuit at normal stator current. The efficiency thus deduced is generally a very fair approximation to the true efficiency, but in large machines may be somewhat too low.

When the specified performance of the generator refers to the *true* efficiency, it becomes necessary to determine the total losses actually occurring under conditions approximating as nearly as possible to those of normal operation. In rare cases it may be possible to measure the mechanical input by means of a torsion dynamometer; but in general practice the principle methods available are: (i) the wattless current method, (ii) the air-heating method, and (iii) the Hopkinson test.

In making a *wattless current* test the alternator, uncoupled from the turbine, is run up to full speed, either by the use of an auto-transformer or a temporary belt drive, excited to normal voltage, and connected in parallel with any available machine or power-circuit of the same voltage and frequency, and capable of absorbing the full output of the generator under test as a wattless current, while supplying a power current equivalent only to the losses to be measured. The alternator then continues to run as a synchronous motor, taking a current at practically unity power factor sufficient to supply the open-circuit losses. Upon increasing the exciting current, a wattless leading current is taken from the system; and by a suitable increase of excitation (and a reduction of that of the machines in parallel, if necessary to maintain normal voltage), the wattless current is made equal to the full-load current of the alternator under test. At the same time the power component of the current increases to correspond with the total losses of the machine on load, which can therefore be directly measured by means of wattmeters in the supply circuit. The total loss thus observed is generally somewhat greater than that obtaining when the generator is working at normal power factor, for the induced voltage and flux, the stray losses, and the exciting current are all increased at zero power factor. The excitation loss may be corrected to normal conditions by calculation, and the increased flux is partly offset by the fact that there is little distortion of the flux density wave and therefore a smaller tooth loss in the zero power factor case. As a general rule the total losses are not more than 10 per cent greater than in operation at the higher power factor.

The *air-heating* method in its simplest form can be used only with

machines of the enclosed type,* but is then probably the most reliable means of testing available. The method is applicable to measuring the total loss in a machine under any condition of operation whatever; and, for the purpose of determining the true efficiency, the test is carried out while the generator, driven by the turbine, is in actual operation and supplying full-load at normal power factor. To the air outlet from the stator frame is fitted a chimney of such form and length as to render the flow of air steady and approximately uniform. The area of the top of the chimney is divided into a number of equal squares, over each of which the velocity of the air is measured by means of an anemometer or equivalent apparatus. From the average reading, and the area of the chimney, the total volume of air (V cubic feet per minute) is calculated. The mean temperatures of the air at inlet (T_i) and at outlet (T_o) are also observed by means of standardized thermometers. If the load on the station is variable, the output of the unit under test must be held practically constant by hand regulation of the governor and field rheostat, and the various readings are taken only after the temperature rise of the air has become absolutely constant. The total losses absorbed by the ventilating air, between the points at which the inlet and outlet temperatures are measured, is then given by:

$$\text{loss in kilowatts} = \frac{V}{1650} \times \frac{273}{273 \times T} \times (T_o - T_i),$$

where the temperatures are expressed in degrees centigrade. The power thus obtained, of course, excludes bearing friction, or other loss external to the air system, such as in the exciter or in field rheostats. The bearing friction may be accurately measured by observing the losses, when the machine is driven *unexcited* by means of a motor, both by the input to the motor and by the air-heating method; the excess of the former over the latter gives the bearing losses. When due precautions are taken the method is capable of ample accuracy for efficiency tests.† A possible source of error is in the radiation of heat from the frame, whereby a small part of the loss is dissipated without entering the cooling air; and approximate allowance for this minor effect is given by: kilowatts radiated = external surface of frame and end-covers in square inches $\times$ T $\times$ 10^{-5}, where T is the mean difference of temperature between the frame and the surrounding air in degrees centigrade.

The *Hopkinson* test affords a means of determining the efficiency of a machine at unity power factor with an expenditure of power equivalent only to the losses; but the method is only applicable when two identical generators are available. The two machines are mechanically coupled together, with a small difference of phase between the rotors, and are arranged to be driven

* See, however, R. Threlfall, "The Testing of Electric Generators by Air Calorimetry", *Journal, I. E. E.*, Vol. 33, p. 28, for a successful application of the same principle to an open-type alternator.

† For details of procedure, see S. F. Barclay and S. P. Smith, *Journal, I. E. E.*, Vol. 57, p. 293.

by a calibrated motor of sufficient power to supply the full load losses of both machines. When the set is run up to normal speed, and equal exciting currents are supplied to the two field magnets, a pure power current circulates between the two stators (Art. 7, p. 19), one machine acting as a motor and the other as a generator. If a suitable phase displacement has been used, full-load current will be obtained with normal terminal pressure. The electrical input to the driving motor, less the known losses therein, then represents full-load losses in the two alternators.

It has been explained in Art. 1 that the possible efficiency of an alternator depends upon such factors as the initial cost and the temperature rise, besides the operating conditions of voltage, frequency, and power factor. The curves of fig. 1 show the *true* efficiency to be expected in modern three-phase water-wheel generators designed for a temperature rise in accordance with either British or American standard rules (p. 54), and operating at 6600 volts, 0·8 power factor (lagging), and a frequency of 50 cycles per second. When the efficiency tests are to be made by loading the generator on a water resistance, it is necessary that the efficiencies be stated also for *unity* power factor; approximate values may be obtained from the efficiency at 0·8 power factor (lagging) by assuming that the total losses at unity are three-fourths of the losses at 0·8 power factor.

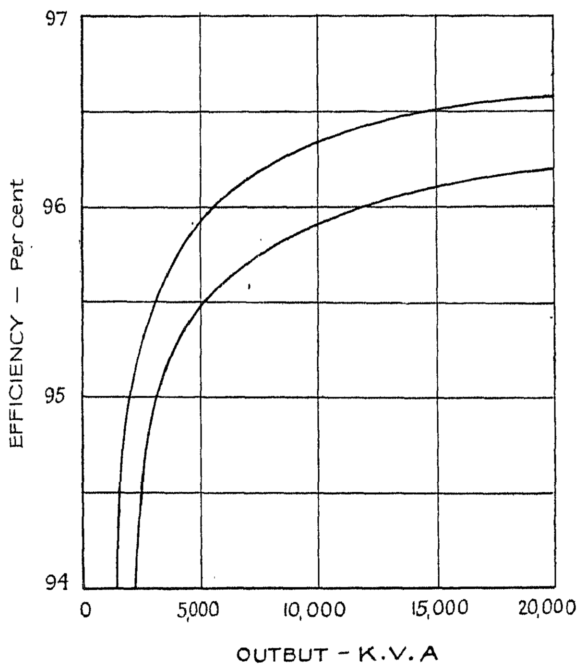


Fig. 1.—True Efficiency of Three-phase Water-wheel Alternators

6. Ventilation.—A portion of the loss occurring in an electrical generator is conducted to the air in contact with the external surfaces of the machine, and is carried off by convection currents and by the natural circulation of air in the station; but the bulk of the cooling is effected by the more rapid current of air passing through the interior of the machine. This cooling air is to be regarded as performing a dual function: firstly, of abstracting heat from the surfaces of those parts of the generator in which losses occur; and secondly, of absorbing and carrying off that heat. The former action necessitates a difference of temperature between the heated surface

and the air-stream in contact with it, and depends for its magnitude upo the area and roughness of the surface, and upon the *velocity* of the curre of air. The latter action involves a rise in temperature of the cooling a itself, the extent of the rise depending upon the total *volume* of air per minu which passes over the heated surface. The actual temperature rise of th surface considered, above the station temperature, is clearly the sum of th temperature rise of the cooling air and the difference of temperature betwee the air and the surface. Hence, in order that the temperature rise may b kept within appropriate limits, it is necessary that a certain quantity of air per minute be passed through the machine, and at a sufficient linear velocity. The movement of air at high velocity over rough surfaces requires a considerable drop of pressure; and the product of this pressure drop into the volume of air passed per minute represents an amount of power which has to be supplied mechanically to the air, and which is ultimately dissipated as heat. Efficient design of the ventilating system therefore consists in the provision of a suitable ratio of air volume to velocity, and a suitable ratio of surface area to mass of active material, in the avoidance of ineffective losses of pressure (as by sudden changes of velocity or direction), and in bringing as much as possible of the cooling air into close contact with those parts of the machine in which the principal losses occur.

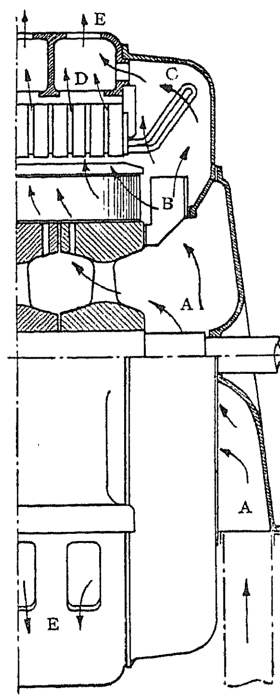


Fig. 2.—Radial System of Ventilation

Water-wheel alternators, almost universally, are ventilated upon the *radial* system, which is shown diagramatically in fig. 2, and further illustrated by figs. 1, 2, and 3 of Chap. IV, p. 58. The present diagram shows the arrangement of an enclosed machine, in which the ventilating air is circulated by fan blades mounted on the rotor. The machine is symmetric about the vertical centre line, the air entering at each end by inlet duc (A, A), which should be so formed as to allow the air uniformly free access the whole of the inner periphery of the fan. In passing between the fa blades (B) the air receives a high radial and peripheral velocity, so that strong current of air impinges on the inside of the stator end winding, ar a pressure of air accumulates in the end guards at C. A portion of the a passes between the stator coils, and discharges through a number of hol (D) into the back of the frame. The remainder passes between the fie coils and along the air-gap, and thence, through radial ventilating spac in the stator core, into the back of the frame. In horizontal sha generators, the air generally leaves the stator frame by a number openings as shown at E. In vertical shaft machines, the same gener

system is usually adopted, except that inlet trunks are frequently dispensed with, and the construction of the frame is often modified so that the cooling air discharges through openings at the lower side only, and is led away by ducts formed in the foundations. This arrangement is illustrated in fig. 3 of Chap. IV, p. 61.

The iron loss in the stator core and teeth is partly conducted radially along the stampings to the external cylindrical surface of the core (whence it is radiated to the surrounding air), partly to the inner cylindrical surface from which it is abstracted by the rapid peripheral current of air carried round by the rotor, and partly by axial conduction (across the laminæ) to the surfaces of the ventilating ducts. The temperature in the interior of a packet of laminations is thus always greater than any of the surface temperatures.

The copper loss in the slot portions of the stator winding is dissipated both by transverse flow through the insulating tube to the stator iron, and by axial flow along the copper to the end connections. In long machines the loss is carried off mostly by transverse conduction, in short machines mostly by axial flow; in average practice, however, both means have to be taken into account. The copper loss in the end connections, together with heat conducted from the embedded parts of the coils, is largely taken up by the direct current of air from the fans, which impinges on the inside of the winding; but further cooling is done by that part of the air which passes behind the end connections and is discharged at the frame holes D. Stray losses produced in the core end-plates are also taken up by the latter stream of air.

The rotor copper is cooled principally by the strong radial current of air through the fans passing over the ends of the field coils. The air which passes axially between the poles is comparatively ineffective, on account of its low linear velocity due to the restriction occurring at the entrance to the stator vents. A part of the field copper loss also flows into the iron body of the poles, and, together with stray losses occurring in the pole-face, is abstracted by the high-velocity current in the air-gap. With very large pole-face losses this action may be reversed; and, in any case, such losses increase the temperature of the field winding. The relative degrees of ventilation of the stator and rotor windings may be to some extent controlled by means of the frame openings at D; increasing the area of these holes tends to reduce the temperature of the stator winding and to increase that of the rotor winding, while closing the holes has the reverse effect. The air is also heated by friction in passing over the various cooling surfaces within the machine, and by violent eddying motion set up in the air-gap, to an extent corresponding with the total ventilation losses, i.e. the sum of fan power and true windage.

In very long machines with few poles, it may not be possible to supply a sufficient quantity of air to the radial core vents *via* the air-gap and the spaces between the field coils. A further supply of air and additional cooling surfaces are then provided by axial holes passing through the laminations.

The amount of power consumed in raising V c. ft. of air per minute to a pressure equivalent to a volumn of *h* in. of water is ·000117 V*h* kw. The total temperature rise of the cooling air in enclosed machines built to meet either British or American standard temperatures is usually about 20° C. Hence, taking the total losses indicated by the efficiency curves of fig. 1 (allowing 10 per cent of the total loss as bearing friction and 10 per cent for heat radiated without entering the cooling air), it is found that the necessary air volume for large machines is approximately V = 350 c. ft. per minute per 1000 k.v.a. normal output. In small machines the lower efficiency is compensated by a greater proportion of the loss being dissipated by the frame. The air pressure varies considerably; but a low pressure is usually associated with a low fan-efficiency; and an approximately representative result may be obtained by assuming a pressure of 5 in. water-gauge in the end guards, in combination with a fan efficiency of 40 per cent. Then the total ventilation loss becomes ·000117 × 350 × 5/0·4 = 5 kw. per 1000 k.v.a. normal rated output of the generator.

7. Heating.—Continuity of service in an alternating-current generator, apart from occasional attention to mechanical requirements such as wear of bearing liners or the tightening of winding clamps, becomes almost entirely a question of the permanence of the insulation. Accidental imperfection of the insulation at any point may, of course, lead to failure very shortly after the machine is first put into operation; but such weakness should be revealed by a pressure test and measurement of the insulation resistance of the hot winding after the generator has run on short-circuit for several hours, and as a rule may readily be rectified. A more serious cause of breakdown in high-voltage machines may arise from the formation of nitric oxides or of ozone, due to electric discharge across narrow air spaces, either between the conductors and the inside of the insulating wrapper, or between the outside of the insulation and the iron core. This action occurs only when a critical value of the electrostatic field in the air space is exceeded, which results from the use of too thin a covering of solid insulating material. The results are particularly disastrous when nitric oxides are formed *inside* the wrapping; and all internal air spaces should therefore be particularly avoided. At pressures exceeding about 8000 volts to earth, however, it is very difficult to avoid the formation of a trace of ozone at the ends of the slots and at the edges of radial vents, at which points the dielectric stress is a maximum.

Passing over, however, these several causes of failure, which are to be avoided in the design or in the construction of the generator, the length of time during which the insulating materials are capable of retaining their essential electrical and mechanical properties depends primarily upon the *temperatures* that these materials attain in the working of the machine. The effect of prolonged subjection to a high temperature is mainly to destroy the mechanical strength, flexibility, and toughness of the materials; disintegration then follows, as a result either of the slight but rapid vibration which is always present in an electrical machine, or of an abnormal shock due to

sudden short-circuit; and ultimately electrical failure takes place. Breakdown may also occur, without previous mechanical damage, in the portions of the stator winding nearest to the terminals, due to an excessive rise of pressure in switching operations, or to electrical disturbances on the transmission system; but the effect of high temperature upon the dielectric strength of the insulation is generally much less important than its destruction of the mechanical properties.

For such reasons failure of the insulation if excessively heated is almost equally to be expected at any point of the winding; and the temperature which has to be considered in this connection is therefore the temperature of the *hottest point* in each kind of insulation. The positions of the hottest points in any one machine vary with the condition of working. On normal load, in order that heat may flow from the embedded stator winding both radially and axially, the copper necessarily reaches a higher temperature than the surrounding iron, and the hottest point of the winding generally occurs about midway between the two ends of the core, and on the top conductor in the slot. On short-circuit, although the stator core carries very little flux, the iron near the extreme ends of the core may be considerably heated by stray losses in the teeth and core end-plate. In consequence of this, the stator copper near the ends of the slots may reach a much higher temperature than on normal load. On open-circuit the temperatures of all parts of the armature winding are much lower than on load. In the field winding, the temperatures within the body of the spools are higher than those of either the inner or the outer surface; the maximum generally occurs somewhat nearer to the inner surface, approximately midway between the two ends of the machine.

8. * Measurement of Temperature.—While the safe working load of a machine strictly depends upon the highest temperature attained at any point, in practice this maximum temperature cannot be directly observed; for, in the first place, it occurs on the inner surface of the insulating wrapping and therefore in contact with conductors working at a high potential, and secondly, because the location of the hottest spot in any particular machine is not known. The maximum temperature can thus only be deduced from a consideration of such temperature readings as are conveniently obtainable; and the probability of a reliable result is to be increased by making a large number of observations in those parts of the machine which, from experience and theoretical considerations, may be presumed to contain the hottest points.

Three methods are available for temperature measurements in electrical machines, namely: (1) embedded temperature detectors, (2) the resistance method, (3) thermometers.

The closest approximation to the maximum temperature is given by *embedded detectors*, which may be either thermocouples or resistance ther-

* In connection with Arts. 8 and 9 the reader should consult: *British Standardization Rules for Electrical Machinery*, 1917, Report No. 72, British Engineering Standards Committee; and *Standardization Rules of the American Institution of Electrical Engineers*, 1918.

mometers. The former consists of two thin wires of different metals—usually copper and constantan (a copper-nickel alloy)—welded together at their ends so as to form a closed circuit, the copper lead containing a galvanometer. When one junction is raised to a higher temperature than the other, an electro-motive force proportional to the difference of tem-

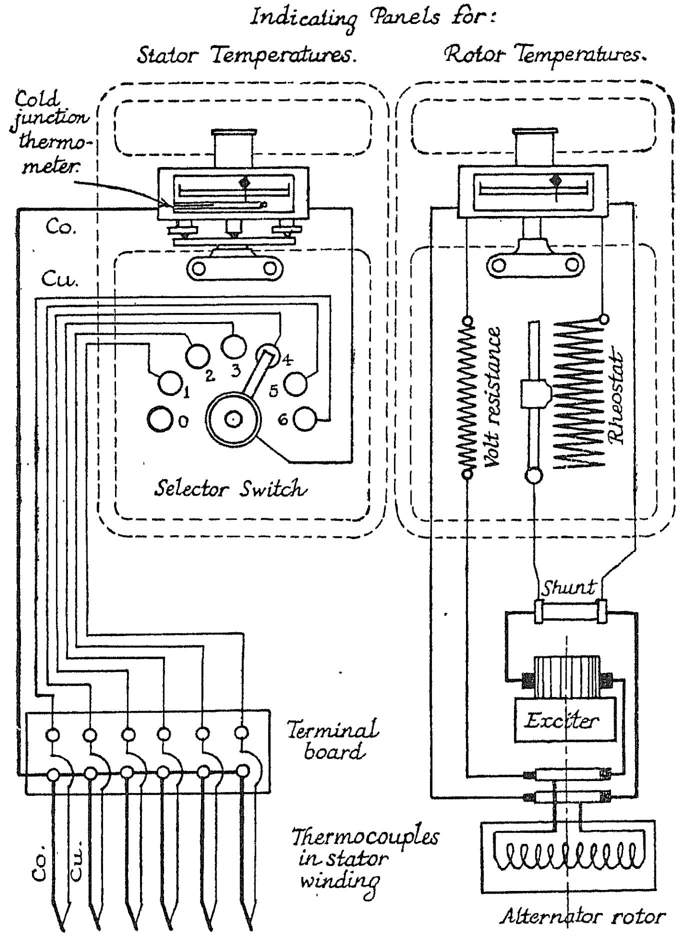


Fig. 3.—Arrangement of Temperature Indicator Equipment for Stator and Rotor

perature (equal to about 43 microvolts per degree centigrade) is produced in the circuit, and the galvanometer scale is calibrated so as to indicate the difference of temperature directly. Fig. 3 shows a complete thermocouple equipment, including galvanometer, a vacuum bottle containing the "cold" junction with a thermometer, and a double-pole multiway switch by means of which any one of a dozen "hot" junctions, situated at different points in the machine, may be connected in circuit. The indicating instrument is provided with a zero adjustment by which the pointer can be set to the

temperature of the cold junction when the circuit is open; the subsequent readings then show the actual temperatures of the hot junctions directly.

The resistance thermometer consists simply of a small flat coil of fine wire, and some form of "Wheatstones' bridge" whereby the resistance of the coil may be measured, the law of variation of resistance with temperature having been previously determined by calibration against a standard thermometer. The change of resistance is indicated by the resulting unbalance of the bridge, as measured by the current in the galvanometer when a known voltage is applied to the bridge. A constant voltage is maintained by adjusting a resistance in series with the battery until the galvanometer shows a standard deflection, when a fixed "unbalancing resistance" is temporarily inserted in one arm of the bridge. A typical output is shown in fig. 4, a multiway switch being used (as with thermocouples) so that the temperatures at a number of points may be read on the one instrument. Neither the thermocouple nor the resistance thermometer has any decided advantage as compared with the other, provided that the resistance coil be concentrated within a very small space. If the coil occupies a considerable length, and especially if it is partly in contact with a well-cooled surface or passes across a ventilating duct, the temperature indicated must be lower than the maximum. The thermocouple, perhaps, has some advantage on the grounds of simplicity, small cost, and general robustness.

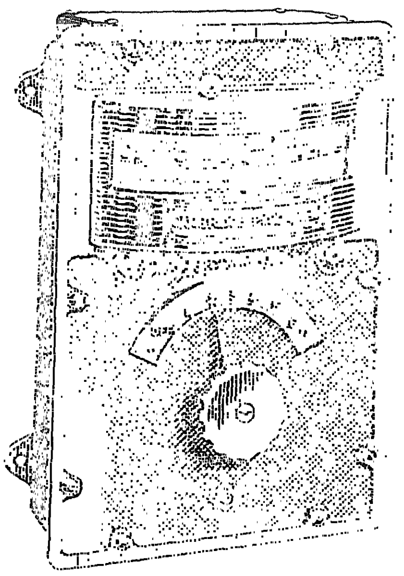


Fig. 4.—Indicator Panel for Thermocouples

It is possible to place temperature detectors of either type in actual contact with the copper conductors, provided that they are placed on one of the conductors immediately adjacent to the neutral point, and that the latter is dead earthed. The highest reading of several detectors so situated gives a perfectly reliable measurement of the temperature of the hottest point in the winding. Since, however, it is not always possible to use a dead-earthed neutral, and since any misplacement of the detector or a subsequent alteration of the terminal connections involves so great a risk of breakdown or danger of shock in making temperature readings, detectors are rarely placed in contact with the conductors except for experimental purposes. For practical safety the detectors have to be placed outside the main insulation, and consequently indicate temperatures appreciably lower than that of the copper. When there is only one coil-side per slot (i.e. when the one or more conductors in the slot are contained within a single insulating cell),

one detector should be placed between the outside of the cell and the slot wedge, and another between the outside of the cell and the bottom of the slot, as in fig. 5 (*a*). The higher of the two readings thus obtained will still be appreciably lower than the maximum temperature of the copper, the error increasing with the thickness of the insulation. In the standardization rules of the American Institute of Electrical Engineers, the maximum copper temperature is taken as the highest reading obtainable by pairs of thermocouples arranged in this manner, *plus* 10° C., *plus* 1° C. for every 1000 volts by which the terminal pressure exceeds 5000 volts.* When two separately insulated coil-sides per slot are used (two-layer winding), the detectors should be placed between the two insulating cells, as shown in fig. 5 (*b*). A detector so placed indicates very nearly the average of the copper temperatures of the two conductors, independently of the thickness of insulation used; and, in the rules referred to, a uniform addition of 5° C. is made in this case to obtain the maximum temperature of the copper.

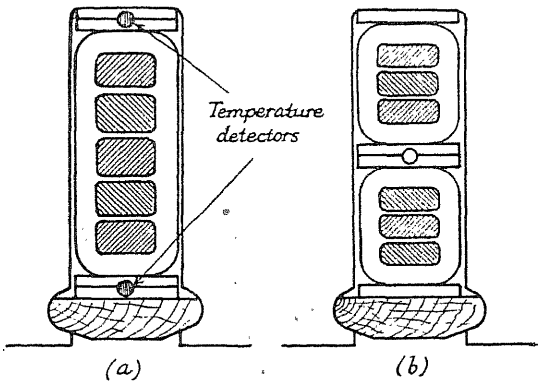


Fig. 5.—Location of Embedded Temperature Detected
(*a*) One coil-side per slot. (*b*) Two coil-sides per slot.

In the *resistance method* of temperature determination the resistance of the stator or rotor winding is used as an indication of its temperature. The principle involved is the same as that of the resistance thermometer described above; but there is the important difference that, whereas the embedded detector is concentrated within a small space, and so indicates practically the temperature of a particular point, the resistance of the entire winding gives a measure of the *average* temperature throughout its length. If R_0 be the known resistance at a temperature of t_0° C., and R be the resistance measured hot, then the average temperature of the winding is given by

$$t = \frac{R}{R_0}(t_0 + 234{\cdot}5) - 234{\cdot}5^\circ \text{ C.}$$

The resistance of the field winding is obtained from the exciting current and the potential difference between the slip-rings (for which separate potential leads must, of course, be used); the rotor temperature can thus be recorded continuously during the operation of the machine.† The resistance of the stator winding, however, can only be readily measured after the machine has been shut down, and by the use of a separate supply of direct

* This allowance is undoubtedly too small. Compare Art. 9.

† An adaptation of the "ohm-meter" has been suggested for showing the temperature of the rotor winding continuously on an indicator.

current. If a sufficient interval of time elapses for the winding to have cooled appreciably, it is necessary to take a series of readings at equal intervals of time, from which the approximate temperature at the instant of shut-down may be obtained by extrapolation. In addition to the fact that the measurement depends upon the temperature of the copper itself, the resistance method has the advantage of requiring only one observation and of presenting a single result free from any arbitrary element as in the location of embedded detectors; but this result, being the *average* temperature of the winding, must always be considerably lower than the temperature of the hottest spot. The difference varies greatly with the size and type of machine, and between different designs for the same rating. The difference is greater in long than in short machines (since in the former the heat developed in the slot portion of the winding and flowing towards the ends has farther to travel), and greater in high- than in low-voltage machines (since in the former a greater proportion of the copper loss is transmitted to the end connections). In the standard rules of the American Institute of Electrical Engineers the temperature of the hottest point of the winding is taken as 10° C. above the result obtained by the resistance method. It is doubtful whether this allowance is sufficient for the type of machine commonly employed in water-wheel units; a higher figure should certainly be used for extra high-tension windings, and for both stator and rotor windings of specially long machines.

The third method of temperature measurement, by means of *thermometers*, although very widely used on the ground of simplicity, cannot be depended upon to give a true indication of the temperatures of the hottest points in the windings. The thermometer can only be applied to external surfaces; that is, to the outside of the field coils, the end connections of the stator winding, and the iron of the stator core. In the case of the field winding, the maximum surface temperature is lower than the average temperature as measured by resistance, and considerably lower than the maximum internal temperature of the winding. In the American rules the maximum internal temperature is taken at 15° C. above the maximum surface temperature. With strap-on-edge field coils this allowance may be sufficient; but in wire-wound coils in which there are several thicknesses of insulating material, through which the heat has to flow to the surface, the internal temperatures are higher.

On the stator winding the thermometer being applied outside the insulation does not as a rule show the temperature of the copper; and being applicable only to the end connections, which are nearly always cooler than the embedded portions, generally gives a result which is considerably lower than the average temperature of the whole winding (or the "resistance" temperature). The slot portions and the end connections, however, require separate consideration. It is possible in some cases for a thermometer placed on the end connections to indicate very nearly the temperature of the copper. Such a result is obtained when the bulb of the thermometer is placed between two adjacent conductors, or between a conductor and a

wooden clamping-block, or at other similar points at which the radiation of heat from the surface of the insulation is greatly restricted.* The temperature indicated is then very nearly the actual temperature of the copper in that region, and this will very often (especially in short machines) be the maximum temperature in the end connections. Although lower than the slot temperatures, this figure may be of greater importance, since it is not always possible to insulate the end connections with materials capable of safely withstanding the same temperatures as the insulation used in the slots. In long machines a higher temperature may occur where the conductors leave the slots, due to the axial flow of heat to the end winding; this reading cannot be accurately obtained by thermometer. The temperatures of the copper in the slots can only be estimated from readings taken on the core iron, on the inner cylindrical surface or on the surfaces of the radial ventilating ducts between the slots (i.e. on the teeth). These surfaces are always cooler than the slot walls, that is, lower than the readings of detectors situated as in fig. 5 (*a*); and temperatures taken on the vent surfaces behind the teeth, or on the external cylindrical surface of the core, are, of course, still lower. As regards the end connections an addition of more than 5° C. may often be unwarranted; and, on the other hand, for the slot copper the allowance should at least include the correction for insulation thickness which is applied to embedded detectors when there is one conductor per slot.

Further, the reading of a thermometer may differ appreciably from the surface temperature which it is intended to measure. The thermometer bulb cannot make good contact with the surface to which it is applied; consequently, if the remainder of the bulb is surrounded by cooler air—and particularly if exposed to a current of air—the reading is much lower than the actual temperature of the surface. This defect may be obviated by covering the exposed side of the bulb with a pad of felt or cotton-wool, but such additional covering hinders the normal cooling, and the surface temperature in that region is increased. The thermometer, however, can never indicate a higher temperature than that of the copper; and unless so much padding is used that the general ventilation of the winding is impeded, the copper temperature cannot be locally increased to any appreciable extent. In the measurement of stator core temperatures it is clear that the thermometer may yield very irregular results, and is particularly unreliable because the error may be in either direction. These difficulties peculiar to the use of the ordinary thermometer may be avoided by substituting for it either a thermocouple or a resistance thermometer. With the former especially it is a simple matter to make a perfectly good contact with the surface, and so obtain an accurate reading independently of exposure to currents of cold air. The hot-spot corrections to be applied remain as for ordinary thermometers, and this application of a thermocouple must not be confused with its use as an embedded detector.

It has already been mentioned that the location of the hottest point of

* Compare the behaviour of an embedded detector with two conductors per slot (fig. 5 *b*).

the stator winding is quite different on short-circuit and on normal load; it is therefore necessary for the stator temperatures to be taken when the machine is working as nearly as possible under rated conditions, and preferably on actual load at normal power factor. For the purpose of works tests, however, any of the methods of operation described in connection with efficiency measurements can be used (see Art. 5). In addition several methods are available in which the normal conditions of heating are approximately realized, but which do not lend themselves to the actual measurement of the losses. For example the stator winding may be connected in open mesh or delta, and full-load current caused to circulate by means of a booster transformer, at the same time that the field is excited to give normal induced pressure. The heating of the field winding may be determined with sufficient accurracy by running the machine on open-circuit at full-load exciting current. The temperature rise on actual load may be slightly higher than on open-circuit, owing to the greater temperature of the cooling air and of the stator face, and to the presence of pole-face losses. If it is inconvenient to make the field heating test at full-load exciting current on account of the large driving power required, when the test is carried out at the maker's works, the temperature rise per kilowatt excitation loss may be found from a test made at a somewhat lower current, and increased proportionately to correspond with the excitation loss on full-load. The field-heating constant cannot, however, be deduced from a short-circuit test, since pole-face losses then form an abnormally large part of the total heat liberated in the rotor.

9. * **Temperature Limits.**—The materials used for the insulation of water-wheel alternators may be divided into two classes as regards their ability to withstand prolonged heating, namely:

Class A.—Impregnated cotton, silk, paper, and similar materials.
Class B.—Mica, asbestos, or other materials capable of resisting high temperatures.

According to both British and American standard rules the temperatures to which these two classes of materials may be continually heated, without loss of their mechanical or insulating properties, are 105° C. and 125° C. respectively. Materials of class B are usually applied in combination with others of class A, both for convenience in applying the insulation and to give solidity and toughness to the complete wrapping. Such composite material may be considered as belonging to Class B provided that, if the class A materials be destroyed by heating, the mechanical and insulating properties of the wrapping are not impaired.

Except in very small machines of which the field coils may be wound with square double-cotton-covered wire and impregnated, the rotor winding almost invariably consists of copper strip wound on edge, consecutive turns being separated by strips of " micanite " (·01 in. to ·02 in. thick), and the entire coil insulated from the pole by a spool built up of micanite or

* See footnote, page 46.

bakelized boards. The micanite separators are composed of small pieces of pure mica built up into a uniform sheet by means of shellac, sometimes upon a paper base, and hot pressed. The shellac remains an effective binding material even after subjection to great heat; but its entire removal in this case causes no defect in the insulation.

The embedded portions of the stator winding (except in very small low-voltage generators) are insulated with a wrapping of " mica-folium ". This material consists of a thin layer of mica, built up of small pieces, assembled on a base of thin tough paper by means of shellac. The requisite number of turns of mica-folium are wrapped loosely round the conductor, and then worked into a very tight and hard rectangular cell by a process of hot ironing, generally combined with steam pressing. Wrappings of this kind may be heated until the paper backing is completely charred, yet the whole remains perfectly sound both mechanically and electrically. It has been found, both by laboratory tests and from experience in the operation of machines having high internal temperatures, that such materials can be worked continuously and with complete reliability at temperatures of 180° to 200° C. As previously mentioned, large high-voltage generators working at standard temperatures as shown by thermometer always have internal temperatures far in excess of the limit of 125° C. previously quoted.* At these high temperatures failure is almost entirely a question of brittleness; and much undoubtedly depends upon the conductors fitting very closely in the slots, the absence of vibration of any kind, and the end-windings being so firmly clamped that, in the event of short-circuit, the projecting ends of the slot cells are relieved from all mechanical shock. In other methods of construction the inner layers of the slot insulation, which are in contact with the conductor and therefore reach the highest temperatures, are of class B materials, while the outer layers which are in contact with the slot walls are of class A. The temperature at which the inner layers are worked must then be so limited that the hottest part of the class A insulation does not exceed the limit specified for that class.

The end connections, being curved, cannot readily be insulated with a mica-folium wrapping, and various materials in the form of tape have to be adopted. The tape may be from one-half inch to one inch wide, depending upon the radius of the sharpest bend to be covered, and successive turns are overlapped by nearly one-half the width of the tape. For generators of moderate voltage, cotton tape impregnated with elastic insulating varnish (such as " Empire cloth ") is commonly employed. Such materials clearly fall under class A. At higher voltages, generally above 3000 volts, it is modern practice to use a " mica-cambric " tape consisting of a layer of pure mica between a cotton tape and a thin paper strip. These tapes will quite safely withstand temperatures considerably in excess of that given for class A materials, and can safely be regarded as of class B, since even if

* For important data and discussion relative to the use of higher temperatures with class B materials, see G. A. Juhlin, "Temperature limits in large A.C. generators", *Journal I.E.E.*, Vol. 59, p. 281.

the cotton basis of the internal layers were to carbonize, the external layers, being at a much lower temperature, would not be injured, and would hold the essential layers of mica firmly in place. Such material is used partly on account of the somewhat higher copper temperatures occurring in a high-tension winding, and partly to obtain a high dielectric strength with a moderate thickness of wrapping. Where space has particularly to be economized, "mica-silk" tape may be substituted. In present practice the temperature of end connections is usually restricted to the standard figure for class A insulation. Consequently it may be found, especially in short machines, that the current-carrying capacity of the stator winding is limited by the temperature of the copper at the ends of the slot cells, where the taping of the end-winding commences, rather than by the much higher temperature obtaining at the centre of the core, where the insulation is of class B.

A matter requiring particular attention is the material used for the insulation between the individual conductors, where several conductors are enclosed within a single main insulating wrapper; for a failure between adjacent strips, whether in series or in parallel, invariably results in the breakdown of the main insulation. Since the temperature of the end connections is in any case limited to that appropriate to class A material, no further restriction can there be required on account of the internal insulation. But in the embedded portions of the coils, if the insulation of adjacent strips consists only of cotton tape, Empire cloth, or similar materials, the maximum copper temperature permissible is that given for class A, and no advantage in this respect is obtained by the use of a mica slot cell. Mica-cotton or mica-silk tape, on the other hand, if containing a considerable proportion of pure mica, can here be regarded as of class B; for if the backing be entirely destroyed, the layer of mica remains in place as effective insulation. Alternately cotton-covered conductors may be impregnated with bakelite varnish, which forms an effective mechanical and electrical separator between adjacent turns, capable of withstanding the temperature appropriate to class B insulation. These remarks apply even where the adjacent strips are connected in parallel, the pure mica being still essential as a heat-resisting mechanical separator although not required for dielectric strength.

10. Temperature Guarantees.—The standard rules of both the British Engineering Standards Association and the American Institute of Electrical Engineers stipulate that the resistance method (Art. 8) shall be used invariably in determining the temperature of the field winding, and whenever possible in the case of the stator winding. For the rotor, the method presents no special difficulty, and has proved quite reliable in practice; but so much difficulty has been experienced in obtaining a dependable reading of the maximum resistance attained by the stator winding, that the method has in this case been largely abandoned in favour of thermometer readings, notwithstanding the well-recognized irregularities of the latter means.

In the American rules, and in those of the British Engineering Standards

Association of 1917 (No. 72), it is stated that, when thermometers are used, the highest reading is to be increased by 5° C. in order to obtain the temperature which would be indicated by the resistance. It has been explained, however, that the difference between the temperatures, shown by thermometer and by resistance, is usually much greater than 5° C., while in certain circumstances the thermometer may indicate very nearly the local internal temperature on the copper, which may be higher than the average (or resistance) value. Owing to this wide range of uncertainty, no completely logical value can be assigned to the necessary allowance; and in the recent revision of the British rules the correction has been entirely ignored, and the limit previously recommended for the resistance method has now been adopted for use with either method. The most modern tendency, however, is toward the use of embedded detectors as the basis of temperature guarantees for the stator, while the resistance method is retained for the rotor, since detectors cannot there be readily applied, and the exact temperature is of less importance, owing to the low voltage. By these two means, a continuous record of both stator and rotor temperature can be obtained during the normal operation of the machine.

Where thermometer readings are employed, it is necessary for the machine to be shut down in order to observe the maximum temperatures on the stator. The temperature then becomes more uniform throughout the winding; and since there is practically no ventilation, the accessible surface temperatures increase. The readings of embedded detectors, and the resistance, decrease upon shutting down.

While the nature of the insulating materials employed sets a limit to the actual temperature which the winding may attain at any point, the output obtainable from a given machine is determined by the permissible *rise* of temperature of the windings above the temperature of the cooling air.* The temperature guarantees of a generator are therefore always expressed as the *rise* of temperature when the machine is carrying normal rated output.

The air temperature, in the case of open-type machines, is usually measured at a distance of a few feet from the frame, and in the direction of the flow of air towards the machine. In enclosed machines, the air temperature is taken in the air duct, at the point of entrance to the generator. Since a considerable part of the cooling is effected by radiation from the frame, the temperature rise is sometimes reckoned from a conventional "ambient temperature", such as: (room air temperature *plus* four times inlet air temperature) divided by five.

The permissible temperature rise is, of course, obtained by subtracting from the limits of temperature, discussed in Art. 9, the probable maximum air temperature at the site where the machine is to be installed. Standard machines are designed for an air temperature not exceeding 40° C. The

* The output obtainable for a given rise of temperature depends also to a small extent upon the temperature of the cooling air, since a higher actual temperature increases the resistance of the windings.

permissible limits of temperature rise, as determined by embedded detectors, are then: 65° C. with insulation of Class A, and 85° C. with materials of Class B. The corresponding maximum *observable* temperatures are then: by the resistance method, 55° C. and 75° C.; and by the use of thermometers (or detectors applied to external surfaces of the finished machine), 50° C. and 70° C.* Large modern water-wheel alternators are frequently designed to work at these limits on normal full-load, and to withstand without injury the temperatures attained in working on an overload of 25 per cent for a limited period, usually two hours, following operation for a long period at normal load. This form of rating takes advantage of the facts that the mica-tape insulation employed on the stator end-connections is undoubtedly superior to the ordinary materials of Class A, while the micafolium slot cells, and micanite field-coil insulation, are unaffected by temperatures far in excess of those standardized for Class B materials.

* The thermometer limits mentioned are those of the Am. I. E. E., and the earlier B. E. S. A. rules; as previously stated, the revised B. E. S. A. rules adopt 55° C. and 75° C. for thermometer also.

CHAPTER IV

Alternator Construction

Description of figs. 1, 2, and 3; stator frame; stator core; stator windings; magnet wheel; pole construction; field winding.

1. Description of Figs. 1, 2, and 3.—In illustration of some of the constructional details described in this chapter, reference will be made to the sectional drawings of three typical water-wheel alternators which are here reproduced. These represent machines of the following ratings.*

Figs. 1, 1a, and *1b*: *2000 k.v.a. 1000 r.p.m.*, horizontal shaft generator; 1600 kw. at 0·8 power-factor; 10,000 volts; three-phase, 50 cycles per second, 6 poles; with overhung exciter, 16 kw. at 70 volts. The machine is one of eight built by the British Westinghouse Electric Manufacturing Company for the power stations at La Pique Supérieure, of the Compagnie d'Électricité Industrielle, France. The rotor is composed of unbored discs with poles integral with the rotor body, and has a special construction of spigoted pole tips; the stator winding is of the concentric type, with end windings arranged in two planes.

Fig. 2 (in pocket at end) and *fig. 2a*: *8000 k.v.a., 450 r.p.m.*, horizontal shaft generator; 6000 kw. at 0·75 power-factor; 4500–5000 volts; three-phase, 45 cycles per second, 12 poles; with overhung exciter, 45 kw. at 100 volts. One of two machines built by the same company for the Societa Anglo-Romana, Italy, for Rome. The rotor is built up of discs pressed on to a shaft, with laminated dovetailed poles; the stator winding has involute coils with full-pitch "wave" connections.

Fig. 3: *20,000 k.v.a., 375 r.p.m.*, vertical shaft generator; 18,000 kw. at 0·9 power-factor; 11,000 volts; three-phase, 50 cycles per second, 16 poles; with vertical exciter carried on shaft extension, 95 kw. at 175 volts. A standard water-wheel unit of the Metropolitan-Vickers Electrical Company, provided with top guide bearing, and a Mitchell thrust bearing carrying the entire weight of alternator and turbine runner, and the hydraulic thrust. The rotor consists of three cast-steel wheels, with dovetailed laminated poles; the stator has short-pitch "lap" coils of the involute type.

All three machines are radially ventilated by fans mounted on the rotor. In each case the overspeed is 80 per cent above the normal running speed.

* By courtesy of the Metropolitan-Vickers Electrical Company of Manchester.

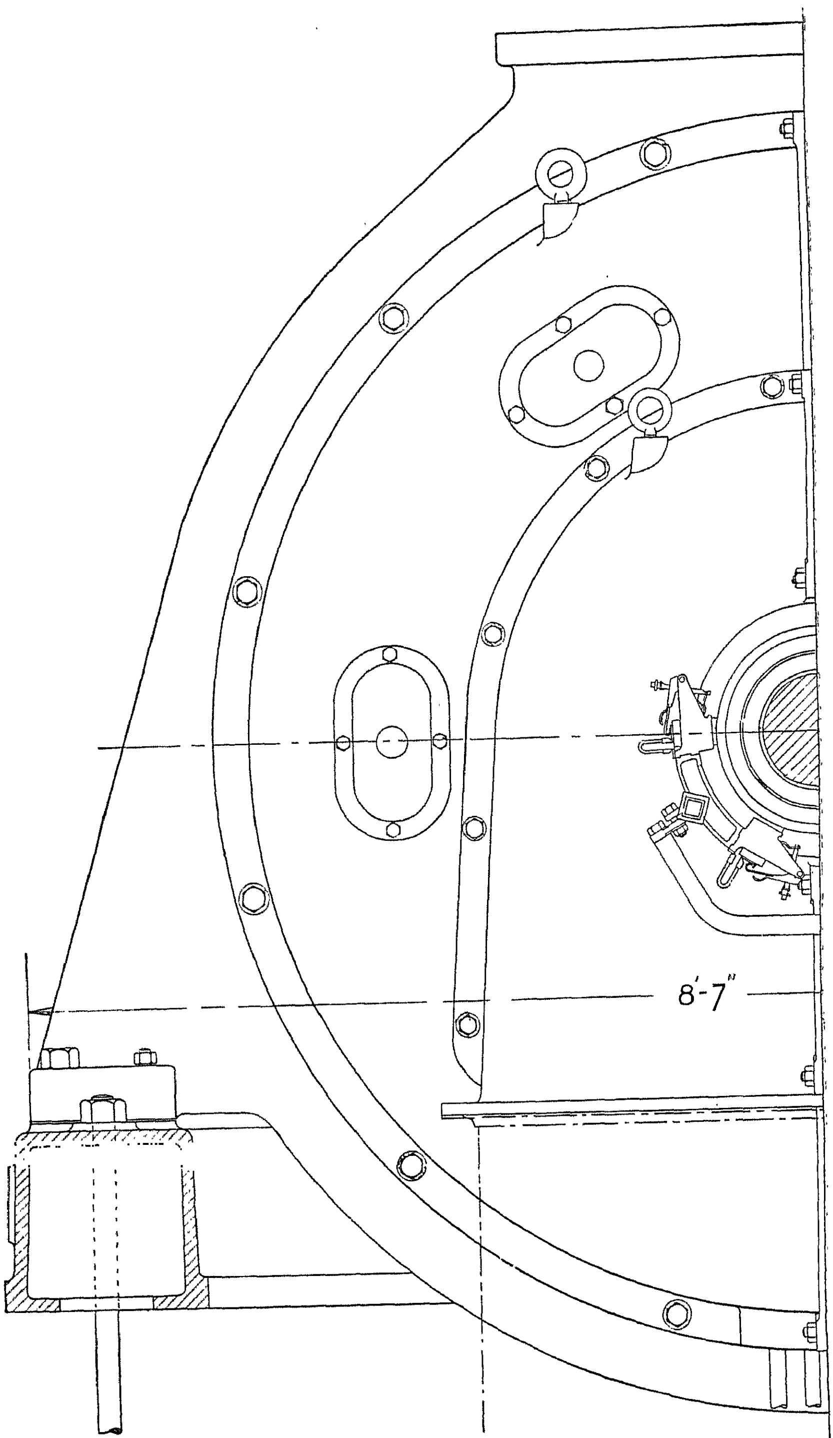
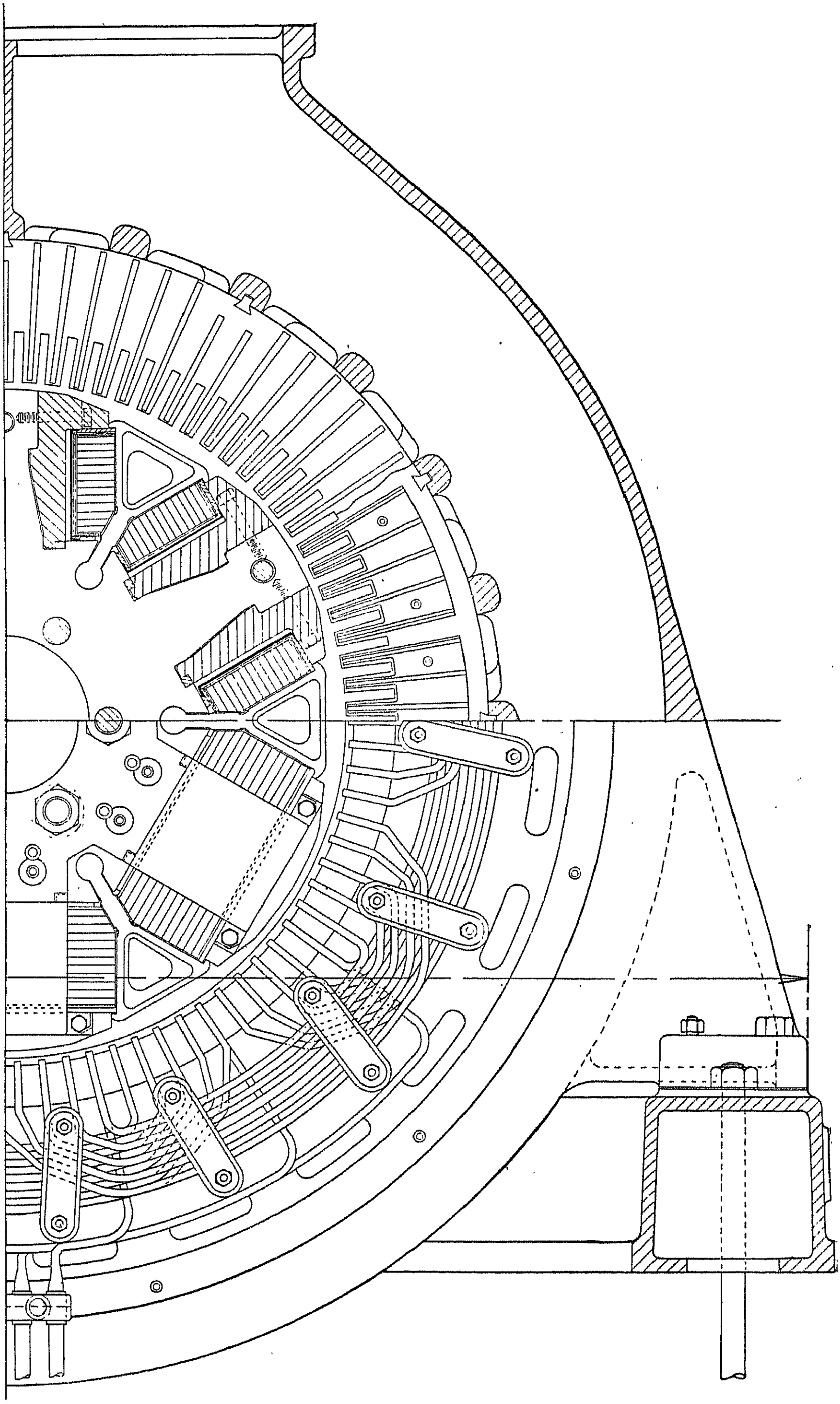


Fig. 1.—Horizontal Shaft Generator. 2000



k.v.a., 1000 r.p.m., three-phase, 50 cycles

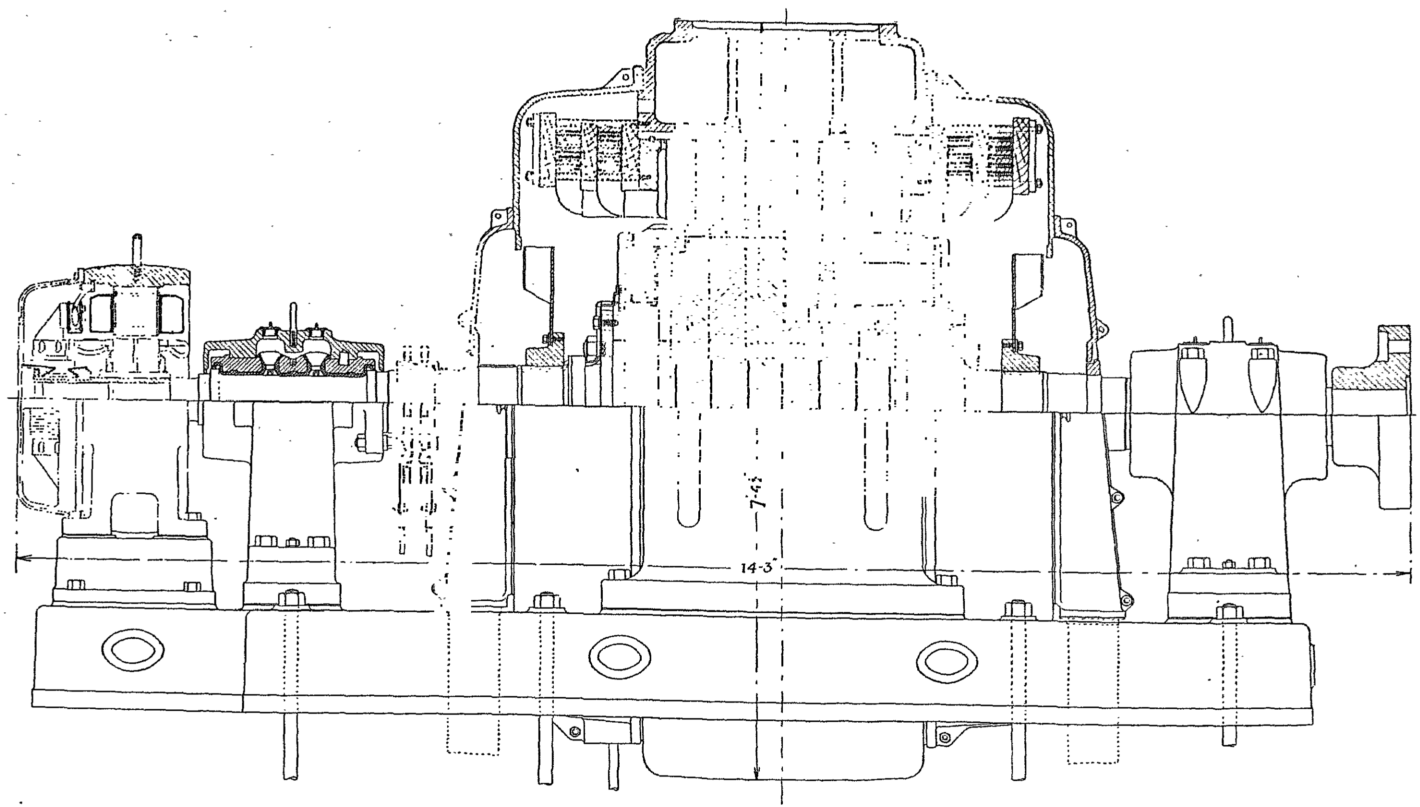


Fig. 1*a*.—Horizontal Shaft Generator. 2000 k.v.a., 1000 r.p.m., three-phase, 50 cycles

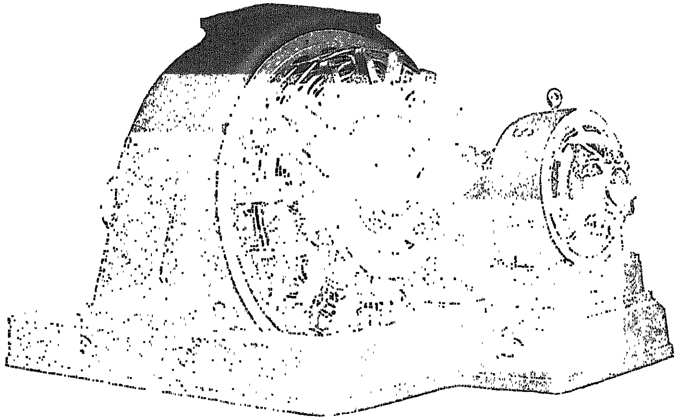
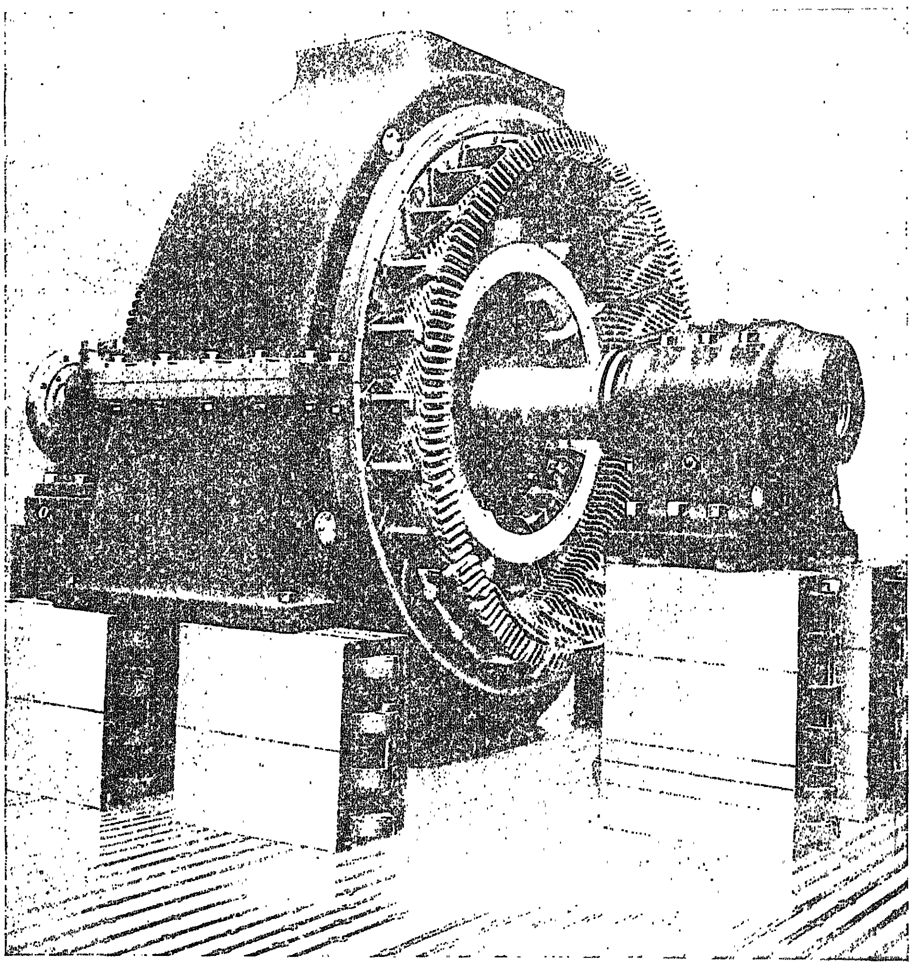


Fig. 1*b*.—2000 K.V.A., 1000 R.P.M., Water-wheel Alternator, End Guards Removed



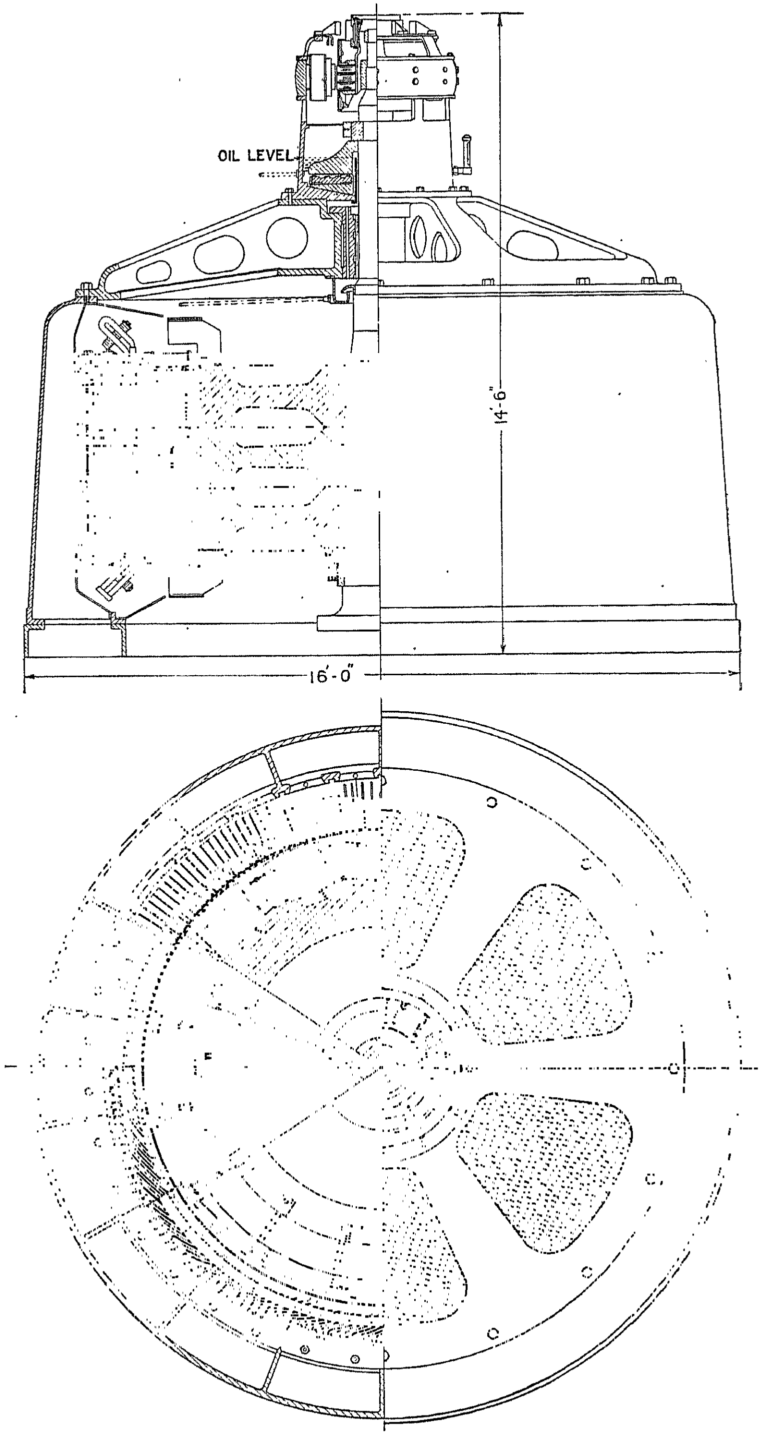


Fig. 3.—Vertical Shaft Alternator. 20,000 k.v.a., 375 r.p.m., 11,000 volts, three-phase, 50 cycles

2. Stator Frame.—This is usually an iron casting of hollow box section, of which common forms are represented by figs. 1, 2, 3, and 4. On the inner diameter the frame carries a number of heavy axial ribs, in which dovetailed grooves are cut to receive the keys on the core stampings. The ends of the frame are so formed as to provide a substantial support for the core end-plates, and are also machined to carry the winding guards or enclosing covers. The outer wall of the frame in small and low-speed machines is perforated by a number of large openings through which the ventilating air is immediately discharged. In large horizontal machines it is usually required to discharge the whole of the heated air either at the top of the frame, whence it is readily carried away by the natural ventilation of the station, or at the bottom, where connection is made to a special duct leading to the outside of the building. The frame is then made entirely closed on the outside with the exception of a single large opening at the top or bottom. In large vertical-shaft machines the air may be discharged at the top or bottom end of the frame; but more commonly the frame has openings in the outer cylindrical wall, the hot air being sometimes collected and carried away by an external sheet-metal trunk. The frame must be of ample section, particularly near the sides of the opening, to allow the discharge of the air without appreciable drop of pressure.

Frames up to about 10 ft. in diameter can generally be made sufficiently rigid to maintain a true circular form when the entire weight of the stator is carried on two main feet, one on either side of the lower half of the frame. Larger vertical frames, however, generally need additional support in order to avoid distortion and consequent unbalanced magnetic forces. The simplest means of preventing such deformation is by the use of one or two auxiliary supports placed under the lower half of the frame; the lower half being thus directly supported, the stiffness of the sides of the frame effectively relieves the bending stresses in the upper half. This method of support is usually sufficient for the largest diameters required in horizontal-shaft water-wheel units.

For ease of casting, except in machines of small diameter, the frame casting is divided on the horizontal, and, if necessary, also on the vertical diameter. The parts are accurately registered at the joints by keys, and secured by a number of bolts passing through heavy flanges. The joint is sometimes more conveniently made by long bolts passing through the frame, as in fig. 4, external flanges being then avoided; but to reduce their elastic extension such bolts need to be of large diameter. Frames for large vertical units are usually made in several sections, only light bolts and flanges being required. Where transport facilities are limited, and where at the same time it is undesirable to build and wind the core on site, it is sometimes necessary to make the frame in several parts, each containing a portion of the core complete in itself, thus allowing easy assembly on site. Where it is possible to carry one-half of the total weight, the frame is best divided somewhat below the horizontal diameter; when three parts are necessary, the upper half may be in one piece while the lower and heavier part is

further divided at the bottom. Exceptionally heavy frames may be made with the feet separate, and the ring divided into four or more sections. For split stator windings see Art. 4.

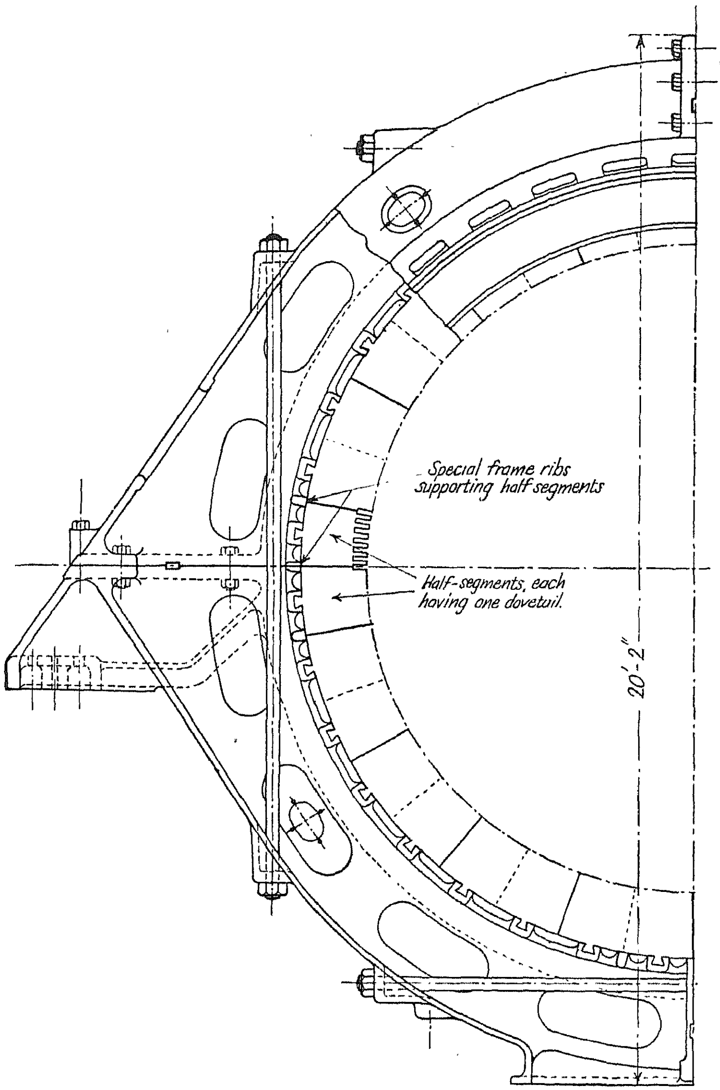


Fig. 4.—Stator Frame, showing Long Bolts and Special Ribs for Split Yoke

The split-frame construction is also often required as giving ready access to the stator or rotor, for inspection or repairs, by removing the upper half of the frame. Alternatively, the complete stator may be arranged to be moved axially by screwgear on extended machined facings provided on the bedplate, sufficiently to expose the whole of the stator and rotor faces. These constructions are open to some objection. The split stator necessitates

an expensive construction of both core and stator winding, and in any case some disconnection of the winding is unavoidable; while the sliding stator needs a longer and therefore much heavier shaft and bearings, and occupies a considerably greater floor space. With dovetailed poles it is usually a simple matter to provide gear by which a pole may be withdrawn axially without dismantling any other part of the machine, thus providing a space sufficient to allow the inspection or replacement of any part of the stator winding.

3. Stator Core.—When the external diameter of the core does not exceed about 4 ft., as in small generators driven by high-speed Pelton wheels, the stampings may be complete circles, provided with a single key to ensure correct alignment of the slots. Larger cores are built up of segmental stampings, each stamping being located by two keyways, separated by one-half the width of the segment. Successive circles of punchings are overlapped by one-half the width of a segment, so that the joints are staggered. The number of segments per circle depends partly upon the dimensions of the sheets of steel economically obtainable, and also upon the number of slots required. If there is an even number of slots per segment the stampings are all identical (fig. 2); but with an odd number of slots per segment two different stampings are required, one-half of the total number having a slot on its centre-line and the remainder a tooth on the centre-line (fig. 1). This may be avoided by using an odd number of key-ways and frame ribs, with segments of such a width that the number per circle is a whole number *plus one-half*; the core is then built up as a continuous spiral.

With a small number of segments per circle, radial movement of the stampings is effectively prevented by their close contact at the joints, and keys of the simple form shown in fig. 1 are then only required for accurately locating the segments and to prevent possible rotation of the complete core. With a large number of segments, however, the segments need to be individually secured to the frame in the radial direction, for which purpose dovetailed keys are necessary. The key may be a separate bar of mild steel, screwed to the frame casting, dovetailed slots being punched in the segments. Alternatively the dovetail may be an integral part of the stamping, fitting into a groove cut in the frame casting (fig. 2). When the complete core has to be split, special half-segments are required on either side of each joint. Since there is only one keyway in each of these small stampings, it is necessary to provide two extra plain frame-ribs on either side of the joint, as indicated in fig. 4.

The core is clamped axially between two cast-iron end-plates. For small diameters, these are made as complete circles, and secured in position by segmental keys engaging with recesses turned in the frame casting (fig. 1). One end-plate is sometimes cast solid with the frame. In machines of large diameter the end-plates are preferably made in segments, and the retaining keys are replaced by bolts, passing behind the core, as in figs. 2 and 3. Bolts passing through holes in the core need to be thoroughly insulated, and to be a very tight fit to prevent vibration.

The core end-plate covers only the part of the stampings lying behind the teeth; and to prevent the teeth themselves from spreading axially and so allowing vibration, additional *tooth supports* are required at the ends of the core. These generally take the form of segmental castings carrying inwardly projecting radial fingers. To reduce stray losses and local heating, tooth supports are usually of bronze. For large machines, the fingers (when of bronze) need to be of very heavy section to give sufficient stiffness; and for this reason are often replaced by malleable-iron castings. Owing to the reduction of section which is then possible, the heating can still be kept within permissible limits by careful design. In small machines the tooth supports may be riveted to the end stampings of the core; but in larger machines are preferable screwed to the inner face of the core end-plate. Fig. 5 (*a*) shows a small cast gun-metal finger-segment riveted to the core stampings; while (*b*) shows the arrangement of a malleable-iron tooth-support suitable for a large generator.

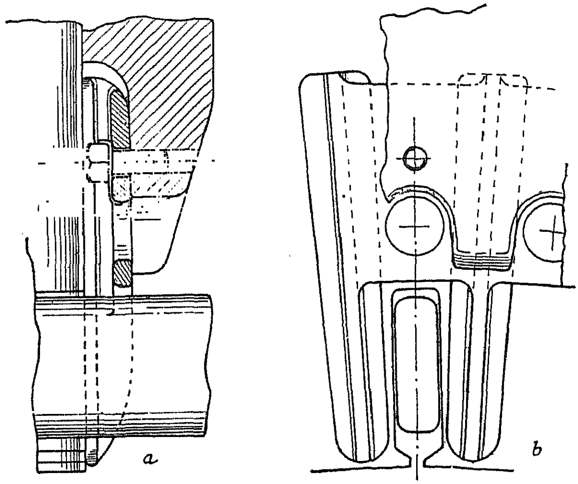


Fig. 5.—Stator Tooth Supports

The radial *ventilating spaces* in the body of the core are formed by separators attached to the core stampings on one side of the vent. The separators are subjected to extremely heavy stresses, and their construction needs particular attention; for distortion or collapse of the separators interferes with the ventilation of the machine and also allows destructive vibration of the core stampings. Vent separators are often made of a "channel" section pressed from $\frac{1}{16}$-in. sheet steel; this form is quite satisfactory in small machines, provided that the separators are accurately formed so that the back of the channel has no initial tendency to collapse, and that they are placed sufficiently near together. Generally, two separators per slot-pitch gives a suitable spacing, one projecting down to the inner edge of the core stamping, so as to support the tooth. In larger machines greater stiffness can be obtained by placing two "channel" separators back to back, or by using a solid mild-steel strip about $\frac{1}{4}$ in. thick. In the latter case the tooth separator should taper to a narrow edge to avoid much restriction of the flow of air into the vent. In most cases the separators are attached to the segments by electric spot-welding.

The stator *slots* are either of the "semi-closed" or the "open" types, seen in fig. 6 (*a*) and (*b*) respectively. With open slots and a suitable type of

winding, the coils can be dropped in complete, which greatly facilitates repairs; but open slots in generators of the water-wheel type usually necessitate the use of laminated poles or pole-shoes in order to reduce pole-face losses (Art. 6, p. 75). With semi-closed slots the coils have to be pushed through from one end, one or both of the coil ends being formed in position; solid pole-shoes, however, may be used. With either type of slot, the coils are retained by wedges of hornbeam or of vulcanized fibre, which fit into recesses or dovetailed grooves in the case of the open slot. In large machines the slots may be provided with an extended " neck " beyond the space required by the conductor, as in fig. 6 (*c*). The neck has several advantages: the leakage reactance is increased, thereby diminishing the sudden short-circuit current (Art. 4, p. 8); the effective width of the air-gap is increased, which improves the ventilation; and a greater clearance is provided between the rotor and the projecting ends of the slot conductors, which reduces the risk of damaging the insulation in assembling or dismantling the machine. A sub-slot (or axial duct behind the conductor) as shown at (*d*), is also sometimes used in long machines, for the purpose of cooling the slot conductors or of supplying additional air to the radial vents near the centre of the core.

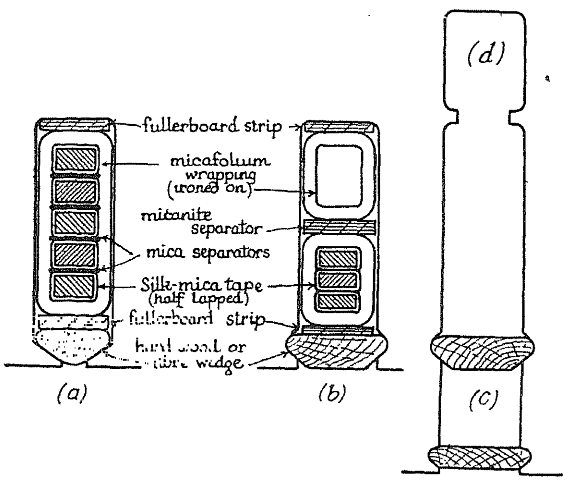


Fig. 6.—Types of Stator Slot and Details of Insulation

4. **Stator Windings.**—Windings suitable for the stators of water-wheel alternators are of two general types: the single-layer " concentric " winding and the two-layer " diamond " winding. The *concentric* winding is composed of a number of similar groups of coils, each group consisting of several coils of different span (or width) placed concentrically one within another, each slot containing one coil side. In the *diamond* winding all the coils are identical, and are arranged uniformly on the periphery of the armature, successive coils overlapping by nearly the width of a coil; one side of each coil lies at the bottom of a slot and the other side at the top of a slot, each slot containing two coil sides. In the concentric winding there is a whole number of coil sides per pole pair, although, for the purpose of eliminating tooth-ripples when open slots are used, the number of *slots* per pole pair can be made fractional by adding empty slots (compare Art. 8, p. 22). In the diamond winding all slots are filled; but the number of slots per pole pair may be either a whole number or fractional.

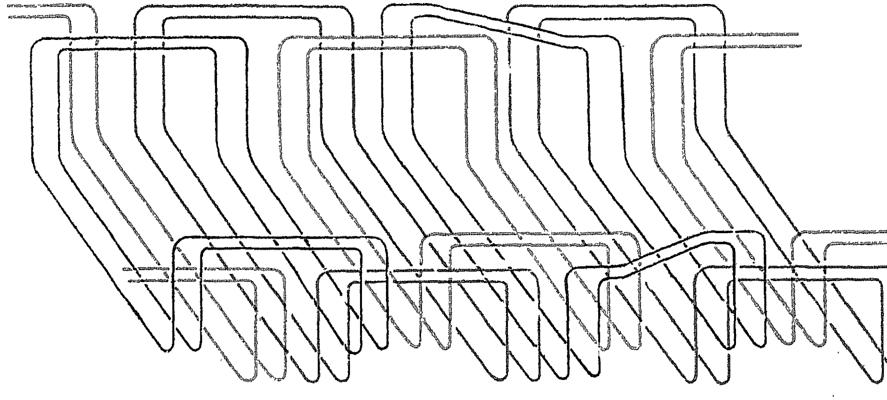


Fig. 7*a*.—Concentric Coil Winding, with 2-plane end connections, for open slots

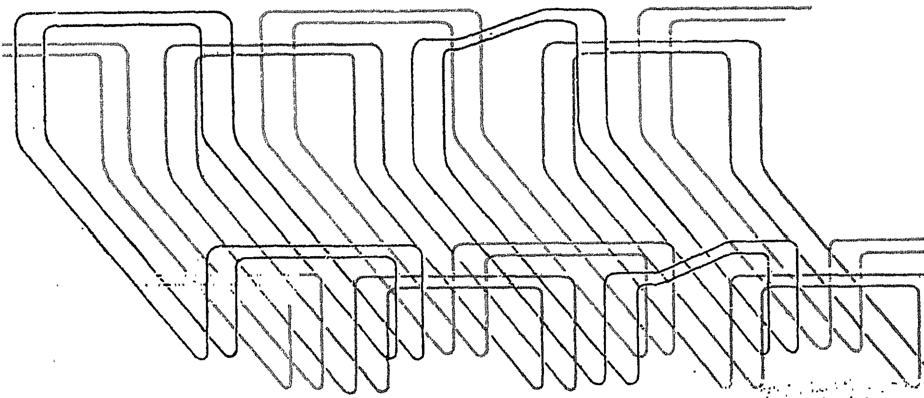
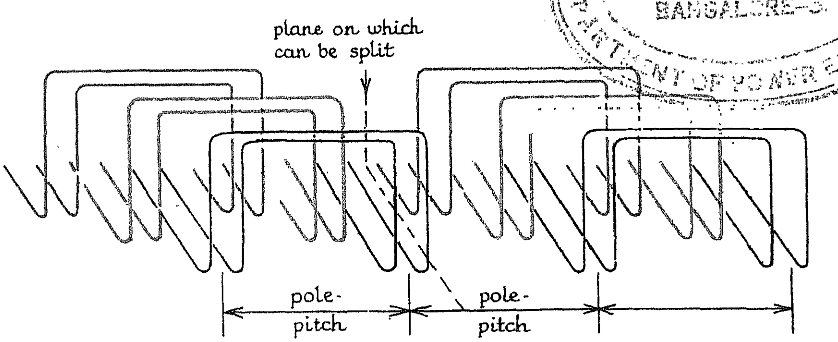


Fig. 7*b*.—Concentric Coil Winding, with 2-plane end connections, for semi-closed slots



For a *single-phase* machine, concentric coils give the simplest possible winding, and are almost universally adopted. The complete group of coil sides per pole usually occupies two-thirds (or rather more) of the total number of slots per pole, the remaining slots being empty. The average span of the coils electrically is equal to the pole-pitch, but the end connections are divided into two groups to shorten the actual length of copper. It is not necessary for all poles of the winding to be identical, which allows of the use of any fractional number of slots per pole pair. Any coil can be removed for repair without disturbing the remainder.

In concentric *polyphase* windings the mean coil-span is a full pole-pitch, and the arc over which the coil sides of each group are spread is limited to one-half of the number of slots per pole in a two-phase winding, and to one-third of the number of slots per pole in a three-phase winding, by practical requirements in the disposition and clamping of the end connections. In a *two-phase* winding the projecting ends of the coils are arranged in two planes. The end connections of a *three-phase* winding can be arranged in either two or three planes. The former method gives the smaller axial overhang of the coils, and is generally adopted in generators of the water-wheel type, since it is simpler in construction and more easily clamped. In a two-plane winding for either two or three phases, the coils may be all of the same length, one end of each coil lying in the plane nearer to the end of the core and the other end in the plane remote from the core, see fig. 7 (*a*), or there may be long and short coils, both ends of the short coils lying in the inner plane and both ends of the long coils in the outer plane, see fig. 7 (*b*). When open slots are used the latter arrangement has the advantage that the coils can be completely formed before winding, the short coils being inserted before the long coils. In the former case the coils are interlinked, and one end of each has to be formed and connected up after the coils are inserted in the slots; but this arrangement is preferable when semi-closed slots are necessary, since only one type of coil is used, and all joints are made in the outer tier. In a two-plane three-phase winding with an odd number of pairs of poles, one group of special coils is required, lying partly in each of the two planes, see fig. 7. By using a three-plane end-winding, with groups *not* bifurcated, and coils of three different lengths, fig. 8, the winding can be divided at several points without opening or removing any of the coils. This type of winding is often convenient where the stator has to be divided for ease of transport but where it is undesirable to build and wind the core on site.

The concentric winding is suitable for any whole number of conductors per slot, connected either in series or in parallel. A fractional number of effective conductors per slot is also obtainable by dividing the winding into several identical parts, and connecting these in parallel. With a single bar per slot,* fully-insulated coil sides are pushed through semi-closed slots, and the coils completed by separate strap end-connectors. With several

* It is here to be understood that each bar may be composed of several laminæ, possibly transposed within the slot, but all solidly joined together at each end of the slot.

conductors per slot, either in series or in parallel but separately insulated throughout the end-connections, the coils may be formed at one end only (giving U-shaped coils) and pushed through semi-closed slots, the overhang at the open end being then formed, and each turn separately connected up and insulated. Alternatively, the coil may be completely formed and insulated at both ends, and dropped into open slots, a single joint per coil then being necessary to connect successive coils in series. In very small machines it is often unnecessary to clamp the end-connections; in this case the outer tier is formed straight (giving plain rectangular coils), while the inner tier is turned up at an angle between 45° and 90° to the axis of the machine. In larger machines, where the overhang has to be clamped, all coils are turned up at right angles to the axis.

The *diamond-coil winding* is not used in single-phase machines. The polyphase diamond winding is uniform over the entire periphery of the armature, as seen in fig. 2, being simply opened at appropriate points to form the beginnings and ends of the several phases. In a two-phase winding each group of coils occupies one-half of the pole-pitch; but in a three-phase winding the phase-spread (or width of each group) may be either one-third or two-thirds of the pole-pitch; see also Art. 8, p. 22. The coils may be either "lap" or "wave" connected. In a lap winding the span of the coils may be less than the pole-pitch by any desired amount, giving a short-pitch or "chorded" winding (Art. 8, p. 22), and the length of copper in the end connections is thereby reduced; with wave winding, the coils are of full pitch. The lap winding necessitates a number of special connections in each pole pair; while in the wave winding the corresponding interconnections are formed naturally by the coils themselves. For this reason wave connections are usually adopted in machines with a large number of poles, and in very small machines; but lap connections are generally preferred where there are comparatively few and large poles, owing to the ease with which any desired degree of chording can be obtained, as well as on account of the smaller total width of the coils, which in large machines facilitates the forming and assembly of the winding. Both lap and wave windings may be used with either a whole number or a fractional number of slots per pole pair. With fractional numbers the groups of coils under successive poles are different. In wave windings with a fractional number of slots per pole pair all coils may be exactly identical, as in a direct-current armature; but with a whole number of slots per pole the winding would close after a single tour of the armature, and a group of special coils is therefore necessary in each phase to form a continuous winding.

Diamond winding obviously requires an even number of conductors per slot; but the effect of an odd or a fractional number can be obtained by connecting similar parts of the winding in parallel. With two bars per slot, in large machines, an "involute" winding is employed, in which the ends of the coils are turned up at an angle of 45° to 60° to the axis of the machine, and take the form of involutes described on a cone; see figs. 2 and 3. Open slots are used, so that the coil may be completely formed and

insulated before dropping into the slots, after which only the joints between successive coils at one end of the machine have to be made and insulated. With very heavy coils it may not be possible to stretch the coil in width sufficiently to enable it to drop into the slots; the two coil sides are then formed separately, and joints made at both ends after the winding is in position. The diamond winding can also be used with two turns per coil; but for more than four conductors per slot a concentric winding is usually adopted in large machines. In comparatively small high-voltage machines, however, an involute winding is often required with a large number of turns per coil; the coils are then wound complete on a former, dropped into open slots, and the single conductor connected up to the adjacent coils at one end of the machine. In small low-voltage machines, with two bars per slot, a simple "barrel" winding may be used, in which the coil ends lie on a cylinder or are turned up at only a small angle. Semi-closed slots are used, the two separately insulated bars pushed through, the ends bent to form wave coils, and the joint made at each end between the two layers by means of a separate clip. Two turns per coil, lying side by side in the slot, can also be used with this type of winding.

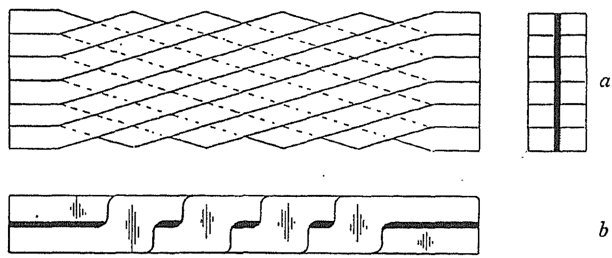


Fig. 9.—Laminated Stator Conductor, showing Transposition of Laminæ in Parallel

The conductors of large machines have usually to be laminated in order to reduce eddy currents (see Art. 4, Chap. III). In concentric windings it is often sufficient to form the conductor of a number of laminæ which are insulated from each other throughout the complete turn of the coil, the increased length of path being sufficient to reduce the circulating current to a permissible value. With larger conductors, however, some form of transposition is necessary. When it is found sufficient to divide the conductor into only two or three parts, the simplest arrangement—suitable only for moderate voltages—is to connect the several laminæ in series, and divide the complete winding into two or three identical circuits, which are connected in parallel. Alternatively, when the individual bars are of considerable section, separate strap end-connections can be used and transposed between the two sides of the coil. When a larger number of laminæ is required, transposition in the end-winding is more troublesome, and cannot always be made complete; it is then preferable to use a special form of conductor in which the strips of each coil-side are crossed within the slot itself. Fig. 9 (*a*) shows a form in which each strip passes gradually from the bottom to the top of the conductor, thus occupying every position; while fig. 9 (*b*) illustrates an alternative construction wherein the strips are crossed at certain

points so that each strip occupies the several slot positions over such lengths of the conductor as to give equal reactances to all strips. In the majority of cases, however, the circulating current in a diamond coil is sufficiently limited by the simple twist produced by the bend at the end of the coil, together with the increased length of path, when the laminæ are separately insulated throughout. In very large machines, however, it may be necessary to transpose the laminæ of the upper bar in the slot, as for a concentric winding, the lamination being retained throughout the complete coil to facilitate the forming of the involute ends.

When an alternator is suddenly short-circuited, the overhanging ends of the stator coils are subjected to very great forces. Damage may result from adjacent conductors being driven forcibly together; but the more serious consideration is that even small movements may injure the projecting ends of the mica slot-cells, and so cause electrical breakdown. To prevent such slight displacements, except in the smallest of water-wheel alternators, the coil ends need to be very firmly clamped in all directions.

In concentric windings (see fig. 1) the turned-up ends of the coils are compressed between the core end-plate and a number of approximately radial clamp-plates, by means of two circles of bolts, the inner circle being situated immediately behind the slots. To prevent heating by an alternating magnetic flux, the inner bolts and the clamp-plates are made of a high-grade bronze; while to prevent the circulation of eddy currents the plates are insulated from the inner bolts. Packing blocks of hard wood, impregnated with insulating varnish, are placed between the inner tier of coils and the core end-plate, between the two tiers of coils, and between the outer tier and the clamping plates. Heavy spring washers are placed under the nuts of the clamping bolts, to compensate for slight shrinkage of the insulation with prolonged heating. To prevent radial movements, the inner coil of a group is supported by micanite bushings surrounding the inner bolts, the concentric coils are separated by narrow packing blocks of bakelized asbestos, and the complete group is clamped by a packing block and wedges driven in between the outer coil and the outer bolts. To give greater circumferential rigidity —which is of primary importance—each circle of bolts is stayed by a complete steel ring, insulated from the bolts. Two rows of small packing blocks are also placed at the bends of the coils, those nearer the core forming a complete circle.

Diamond windings are clamped to cast-iron brackets bolted to the core end-plate, the details being generally similar to those of a concentric winding. Adjacent coils are separated by narrow blocks; but to prevent cumulative movement, a bolt should be placed in every second or third space. Excessive local pressure is avoided by a packing block on either side of the bolt; and additional security is provided at these points by a micanite wrapping on the bolt. This method of clamping is shown in figs. 2 and 3.

5. Magnet Wheel.—The form adopted for the rotor of a water-wheel alternator is determined primarily by the necessary strength to resist the forces of rotation, which vary as the square of the peripheral speed; and

secondly by conditions of transport, which depend upon the diameter and weight of the rotor. The choice between several methods of construction which may then remain as possible alternatives is largely a matter of cost, involving manufacturing facilities and the relative prices of steel in various forms, both of which factors again are influenced by the actual size of the rotor.

For the peripheral speeds, up to about 10,000 ft. per minute,* which occur most commonly in vertical shaft generators, the rotor may consist of a cast-steel (occasionally cast-iron) wheel with arms, to the rim of which the poles are bolted. In order to obtain reliable and uniform material, and to avoid the possibility of shrinkage stresses in casting, the rim is usually made separate from the spider, on to which it is pressed or bolted. Where it is necessary to reduce weight to meet transport conditions, the spider may be divided into two halves or into smaller segments, which are clamped together at the hub by bolts and shrink-rings; while the rim may consist of two or three separate rings mounted side by side on the spider. An example of this construction is afforded by the 32,500 k.v.a., 12,000 volt, 25 cycle, 150 r.p.m. vertical unit built for the Niagara Falls Power Company by the Allis Chalmers Manufacturing Company in 1919.† In rotors of very large diameter it is often necessary to divide the rim also into four segments, in order to overcome difficulties of transport due to its large dimensions apart from weight. The joints between the rim segments are made by bolts and links or shrink-plates.

At higher speeds, where dovetailed poles become necessary, the same type of wheel is usually sufficient up to about 17,000 ft. per minute; but the rim then has to be deeper on account of the space occupied by the dovetails. The necessary depth of rim may be reduced by using two dovetails per pole. Where the rim has to be subdivided, it may be built up of segments of rolled boiler-plate, thoroughly interleaved, and secured by the pole dovetails and numerous bolts.

With increasing speeds, a greater depth of rim is necessary in order to provide a sufficient cross-section below the pole dovetails to carry the main hoop-tension. At the same time the diameter must be kept within limits such that the rim does not need to be divided peripherally. In long machines, two or three separate wheels are placed side by side on the shaft, the pole dovetails passing through the several wheels. A treble wheel of this construction is seen in fig. 3. For further reduction of weight, the rim may be built up of a number of cast-steel rings, of about 4 in. in thickness, each spider carrying four or five such rings, bolted together and pressed into position.

At moderately high speeds, such as 19,000 to 20,000 ft. per minute, so deep a rim is required that it is preferably carried down to the shaft as a solid web. Where further subdivision for transport is necessary, the rotor

* All speeds mentioned refer to the overspeed condition.

† A description of this machine is given in the *Electrical World*, Vol. LXXIV, p. 456; and a detailed drawing is shown by S. P. Smith.

may be composed of flat cast-steel discs, spigoted and bolted together, and pressed directly on to the shaft. A rotor of this type is shown in fig. 2. Somewhat superior mechanical properties can be obtained by substituting discs of rolled boiler-plate, 1 in. to 2 in. thick. With ten or more poles, this form of wheel has sufficient strength for the highest speeds at present required by the water turbine; but the difficulty of obtaining a sufficiently small stress at the bore increases rapidly as the number of poles is further reduced.

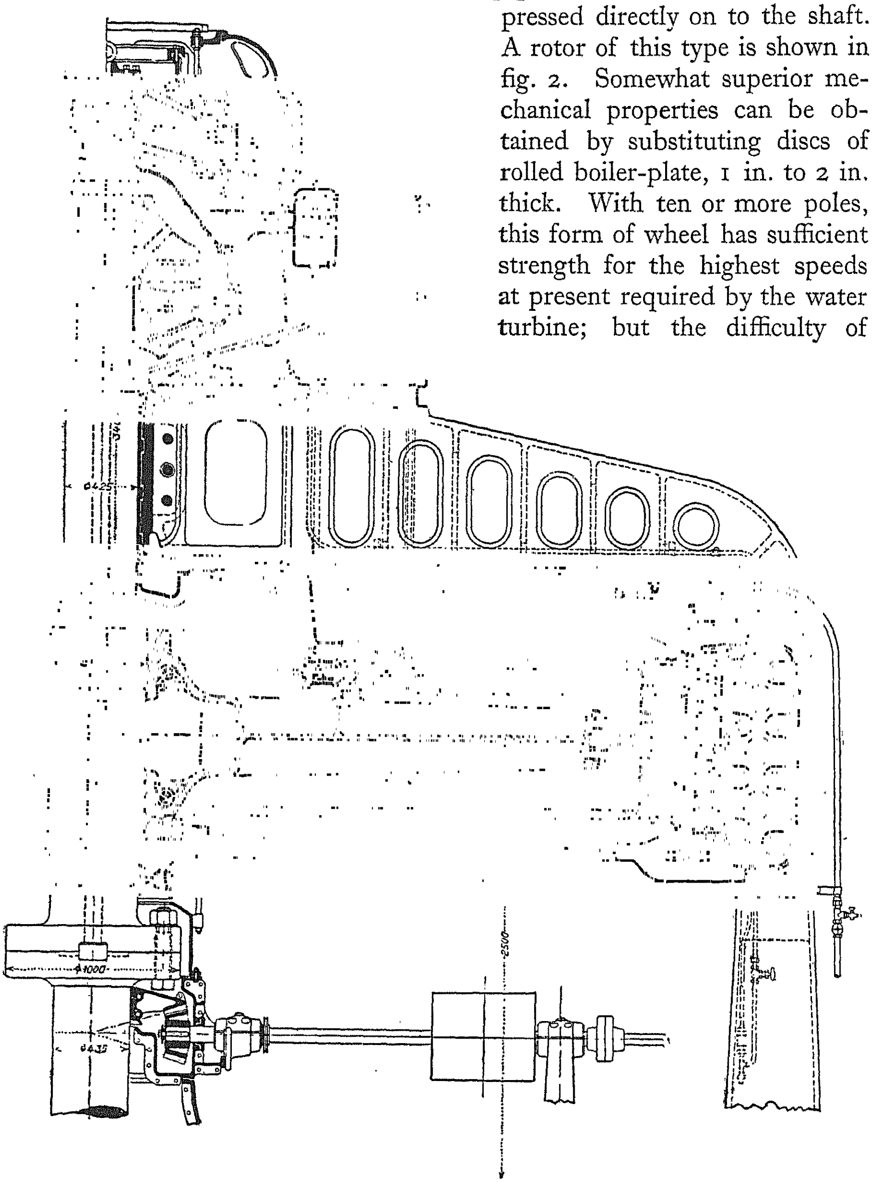


Fig. 10*a*.—7050 k.v.a. Vertical Waterwheel Alternator, by Messrs. Brown, Boveri, & Co.

With eight poles, at 20,000 ft. per minute, a sufficient radial depth below the dovetails is obtainable only by the use of double dovetails, or solid poles integral with the body of the wheel. With six poles at similar speeds, what-

ever form of pole is adopted, no central hole in the wheel is permissible. At lower speeds, as in small machines, a six-pole rotor can be made with a central bore, and solid poles integral with the rotor body. By using a solid unbored disc, the maximum hoop stress is reduced at least to one-half; and a single-dovetailed pole again becomes feasible with 8 or 6 poles. The rotor may then consist of a single steel forging, having disc and shaft-ends in one piece; or the rotor body may be a separate forging, with heavy flanged shaft-ends bolted on. Alternatively, the disc may be built up of cast-steel slabs, spigoted together, and clamped between flanged shaft-ends by a circle of bolts. This last type of wheel is exemplified by the 6-pole rotor shown in fig. 1 Small 4-pole rotors also can be made with solid poles, rotor body, and shaft-ends formed from a single steel forging.

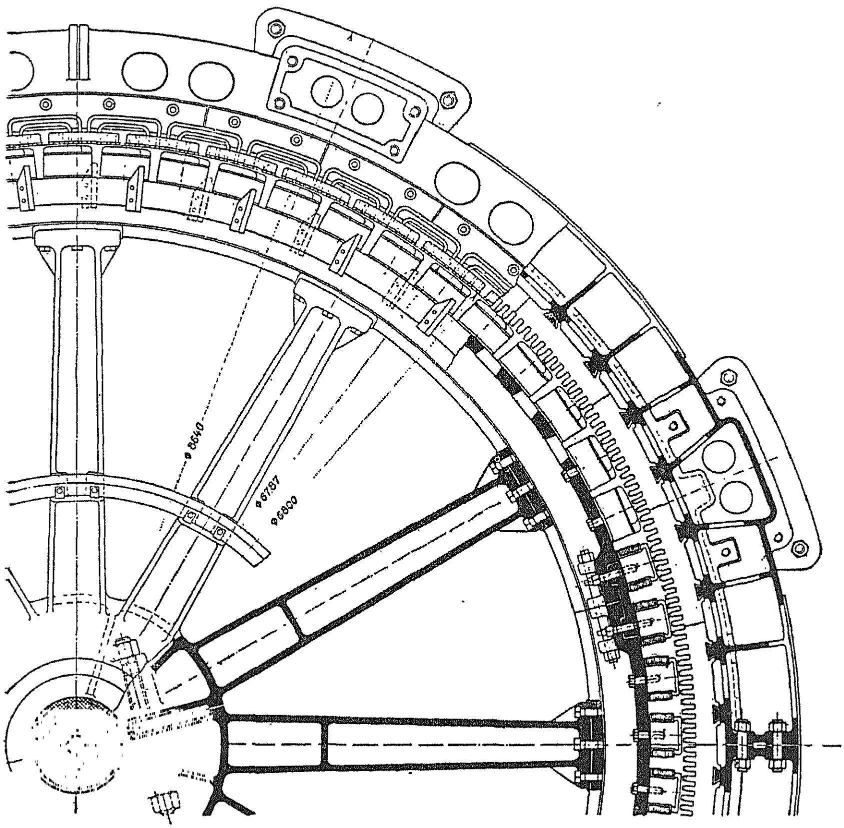


Fig. 10*b*

6. Pole Construction.—At the low peripheral speeds which often obtain in vertical-shaft low-head units, where the possible diameter is limited by conditions other than rotational stresses (compare Art. 6, p. 14), the pole may be attached by bolts passing through the rim of the magnet wheel (see figs. 10*a* and *b*). The poles then have overhanging tips to retain

the field coils; and may be either steel castings, or machined from wrought-iron billets, or built up of laminations. The plates are usually 0·03 to 0·07 in. thick, and are clamped between cast-steel end-plates by several rivets. The pole bolts are tapped into a round steel rod passing axially through the pole. With solid poles the bolts are tapped directly into the pole. In this case the bolts are usually replaced by studs and nuts. The greatest stress occurs in the bolts, which are therefore often of nickel steel. Plate links have also been used, these being interleaved between packets of the pole stampings, and secured by axial keys on the inside of the rim.* With solid poles, semi-closed slots are usually necessary.

At higher speeds, the poles can only be secured by dovetailed projections on the poles fitting into corresponding axial slots in the periphery of the

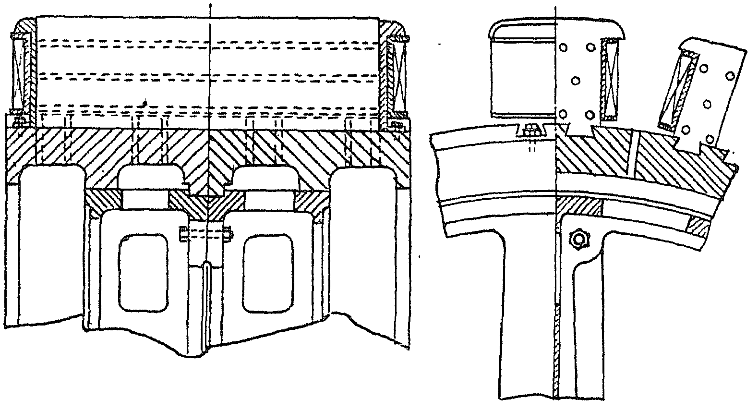


Fig. 11.—Laminated Poles in Halves, each dovetailed to the Rotor

wheel (figs. 2, 3, and 4). This form of pole covers the bulk of modern practice. The dovetails of both wheel and poles are subjected to severe and rather complex conditions of stress, and their design requires much attention in order to obtain the maximum effective strength. The poles are usually laminated, and in the dovetail the plates are subjected to a large component of force in the peripheral direction, which tends to distort the plates as struts; the structure can therefore be treated as solid material only if the laminæ are very firmly clamped by substantial bolts between thick cast-steel end-plates, as illustrated in figs. 2 and 3. The pole dovetail is made narrower than the corresponding slot in the wheel, and is tightened in position by double tapered keys, driven in from both ends, and secured by setscrews tapped into the wheel or by similar means. The dovetails and keys need to be accurately fitted in order to obtain the most uniform distribution of load. To reduce the necessary radial depth of the rim of the wheel, each pole may have two dovetails; it is then necessary to divide the entire pole into two parts in order to ensure an equal distribution of load between the two dovetails.

* Several examples of this construction by Machinenfabrik Oerliken are illustrated by S. P. Smith, "Large Electric Units", British Association (Edinburgh), 1921, abstracted in *Engineering*, Vol. CXII, p. 399, from which article fig. 11 is taken.

An excellent example of this type of pole may be seen in the 32,500 k.v.a., 12,000 volt, 150 r.p.m., 25 cycle vertical unit built for the Niagara Falls Power Company by the Allis Chalmers Manufacturing Company in 1919 (fig. 11).* Solid dovetailed poles are also used. With the width of air-gap commonly adopted, it is then generally necessary to use semi-closed stator slots; or to provide the poles with a laminated surface composed of narrow stampings dovetailed into the solid pole face.

As a general alternative to the dovetailed construction, the poles may be solid and integral with the wheel. The field coils are then retained by solid pole-shoes, made from rolled plate, and attached to the body of the pole by a number of large recessed cheese-headed screws. With a small air-gap, the stator slots are necessarily semi-closed. The greatest stress in such poles is usually that due to bending at the reduced section passing through the centres of the bolts. The shoe may therefore be strengthened when necessary, without increasing the thickness of the pole tips and so reducing the winding space, by recessing the centre of the shoe into the field coil, and ultimately the bending of shear stress in the tips becomes the limiting feature. Bolted-on laminated shoes have been used, but are rarely feasible in water-wheel generators, since it is only possible to distribute the bending moment over the deeper section at the centre by the use of many axial rivets, which in themselves reduce the effective section.

Where open slots are required, the solid bolted shoe may be fitted with a laminated facing, as in the case of a solid dovetailed pole.

For large six- or eight-pole machines, a bolted-on pole shoe is considerably stronger than a dovetailed pole, and at the same time requires less radial depth of rim. At high speeds this construction may therefore render it possible to use a rotor with a central hole, where a solid unbored disc would be necessary with dovetailed poles. In such large machines the wider air-gap often allows the use of open stator slots with a solid pole face.

At the speeds obtained with large high-head Pelton wheels, the linear rotor speed of the generator frequently exceeds the limit at which dovetailed poles or bolted-on shoes are adequate. It is then necessary to form the poles as integral parts of the rotor body, and to secure the field coils by dovetailed pole-shoes or spigoted pole tips. Dovetailed pole-shoes need to be recessed into the poles below the tops of the field coils, in order to obtain a sufficient depth of section to resist bending, and therefore have to be built up in sections, or of stampings. In the latter case, it is essential that the laminæ be very firmly clamped in the axial direction, to prevent buckling under the bending stresses. Fig. 12 shows one of many suitable constructions, in which the stampings are inserted through a slot at the centre of the pole. In the six-pole rotor of fig. 1, separate cast-steel plates carrying overhanging tips are spigoted into the sides and ends of the pole. Lateral clearance is provided inside the field-coil spools to allow of inserting the side plates,

* A full description of this machine is given in *Electrical World,* Vol. LXXIV, p. 456. See also S. P. Smith, loc. cit., p. 403.

which are then secured in their final positions by bolts and axial keys. With this small number of poles, the centrifugal load on the overhanging pole tips is considerably greater at the ends than at the sides of the poles; and the end tips have therefore been further strengthened by being carried down to the rotor body on the outside of the field winding.

Four-pole rotors working at a normal speed of 1500 r.p.m. and liable to an overspeed of 80 per cent, when of small diameter can be made with solid poles, and bolted-on or dovetailed pole-shoes as the peripheral speed requires; but for large machines the standard non-salient pole cylindrical rotor is adopted, as for steam-driven turbo-alternators. Fig. 13 shows the general arrangement of Pelton wheel units of this type, having a capacity of 5000 k.v.a. at a normal speed of 1500 r.p.m. It should be noticed that the severity of the stresses in a rotor having a normal speed of 1500 r.p.m. and subject to an overspeed of 80 per cent, is considerably greater than in a rotor having the same output at a normal speed of 2700 r.p.m. The conditions are approximately those of a machine of 60 per cent greater capacity, working at 2700 r.p.m. with an overspeed of 10 per cent.

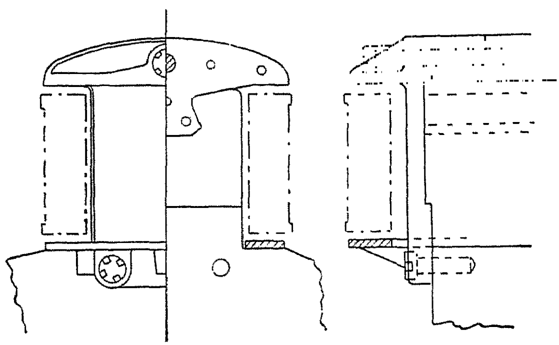


Fig. 12.—Laminated Dovetailed Pole-shoe

7. Field Winding.—The field winding of a water-wheel alternator almost invariably consists of single spiral coils of flat copper strip wound on edge. This construction is adopted on account of the mechanical forces to which the winding is subjected. The centrifugal force on the side of the coil acts in a radial direction, and therefore has a main component parallel to the side of the pole, and a smaller component at right angles thereto, tending to increase the width of the coil. The ratio of the transverse component to the main component varies with the number of poles. In machines with large numbers of poles, the transverse force is unimportant, but with small numbers of poles it may be nearly one-half of the total centrifugal force. The main component is carried by the projecting pole tips at the sides of the poles, and by a projecting lip forming part of the cast-steel end-plate at either end; but it is also highly important to prevent any distortion of the coil by the transverse component. Such distortion would produce a tension in the copper itself, resulting in heavy pressure of the coil against the corners of the pole; and, further, would cause the main component of the load to be concentrated toward the inner edge of the strip, the concentration of load being more severe in a narrow strip than in a wide strip. With a wide strap wound on edge the stiffness of the strap itself greatly assists in resisting the lateral force; while any concentration of stress

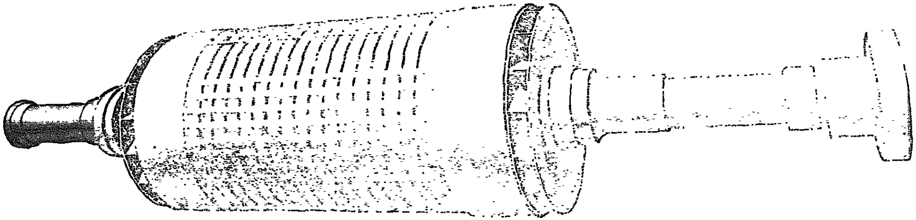


Fig. 13*b*. — Cylindrical Rotor for 5000 K.V.A., 1500 r.p.m., Water-wheel Alternator

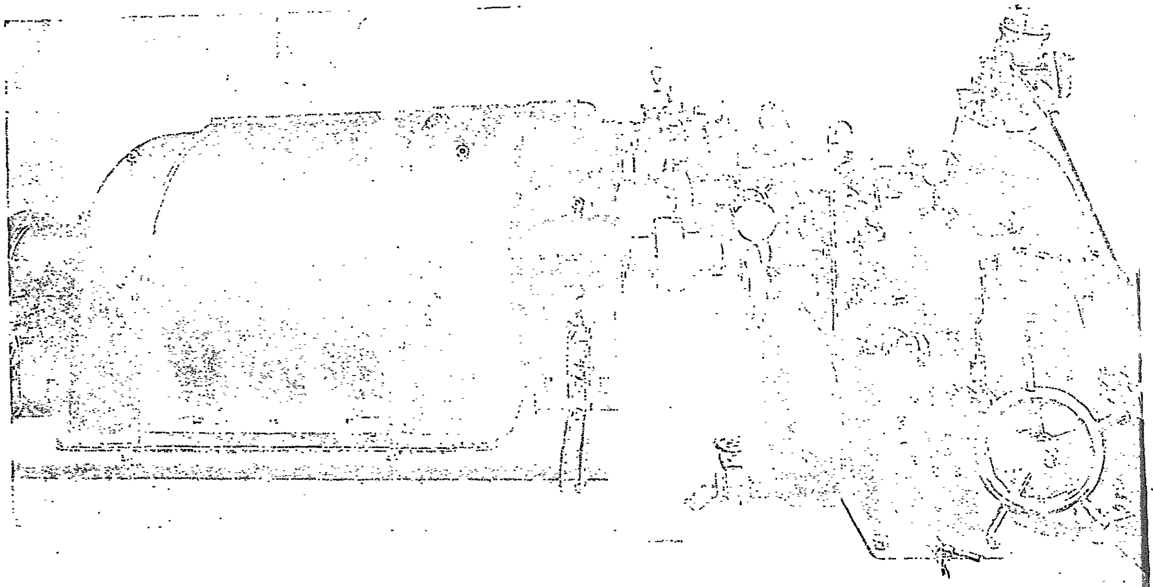


Fig. 13*a*.—General Arrangement of four 5000 K.V.A., 1500 r.p.m., Water-wheel

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due to slight deformation is quite unimportant. Further, in strap-wound coils, consecutive turns can be insulated from each other by means of strips of micanite or of pure mica, which is the only class of material capable of permanently withstanding the stresses obtaining at waterwheel speeds. Coils composed of several layers of square wire are only feasible at low peripheral speeds, and are required only in very small machines with few poles, where a copper strap of the same section would have too great a ratio of width to thickness.

Large field coils are sometimes built upon a sheet-steel spool, from which the winding is insulated on the inside by a wrapping of micanite or similar flexible heat-resisting material, and at the ends by washers of micanite, vulcanized fibre, or bakelized material. Fig. 14 shows a typical construction. The bottom end of the spool is formed by a heavy brass washer, to which the steel liner is riveted. After the coil is assembled and pressed, the steel is turned over the top end-plate and soldered. Between the bottom of the spool and the magnet wheel is placed a cast-brass washer-plate, having lugs which bear upon the sides of the magnet wheel so as to support the overhanging ends of the field coil. This detail is also seen in fig. 14. The spiral coil should be very tightly compressed when the machine is at rest, so that no appreciable movement of the bottom turns under the centrifugal forces occurs when the machine is in operation, otherwise the insulation between turns and between the winding and the pole may be gradually disintegrated.

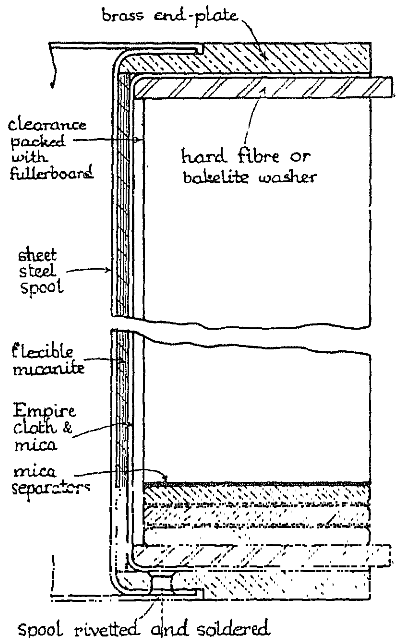


Fig. 14.—Details of Field-coil Insulation

In low-speed multipolar machines, and in short machines working at a moderate speed, the stiffness of the copper strap itself may be sufficient to prevent distortion of the sides of the coils. At higher velocities, or with longer poles, it becomes necessary to insert a V-shaped clamp between adjacent field coils midway between the two ends of the machine. In very long machines two or more clamps may be required. In addition to its own centrifugal force, the clamp is subjected to a radial force which is the resultant of the transverse forces on the sides of the two adjacent coils; which in rotors with few poles may be very important. The coil clamps are usually bronze castings, of such a form as to obstruct the ventilation of the sides of the coils as little as possible. Examples of clamps suitable for large machines are shown in figs. 1, 2, and 3, and in detail in fig. 15. In this case the

radial force on the clamp is taken entirely by a bolt tapped into the wheel; but in other designs the clamp is supported partly by the pole tips.

With a simple spiral coil the connections between successive poles occur alternately at the top and bottom of the poles. The interconnections between adjacent poles need to be firmly supported and clamped. There is a little difficulty in supporting the connecter occurring at the top of the pole; and, to avoid this, the top end may be taken down inside the spool and brought out at the bottom of the pole; the interconnections are then placed alternately at opposite ends of the machine, and can be readily bolted to the magnet wheel. Particular attention should also be paid to the thorough securing of the connections to the slip-rings. The centrifugal force on the radial portion of the leads should be carried by a definite anchoring device, so as to remove all strain from the portion lying along the shaft, which may then be secured by simple cleats.

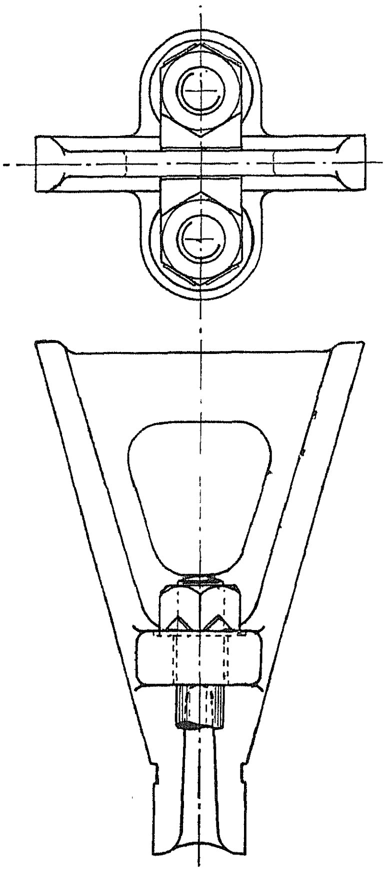


Fig. 15.—Field-coil Clamp

In single-phase machines, and occasionally in polyphase machines intended to work on a considerably unbalanced load, the rotor is provided with a *damping winding*, in order to reduce stray losses (see Art. 4, Chap. III). The damping winding consists of copper bars embedded in axial slots in the pole faces, and connected together at either end by peripheral segments, which are bolted together between adjacent poles so as to form a complete ring at each end. The slots carrying the damper bars are of the semi-closed type, having strong tips so as to retain the bars against their considerable centrifugal force; but wide slot-openings are used, so as to reduce the reactance of the damping winding. The bars are uninsulated, and must fit very tightly in the slots, since they are subjected to a heavy and rapidly alternating electro-magnetic force. They should be tightened in the slots by caulking the copper and riveting over the tips of the slots.

The spacing of the damper slots is a matter of much importance. If the number of damper bars is one more or one less than the number of stator slots in the width of the pole face, the damping winding tends to eliminate tooth-ripples from the wave form of the terminal pressure; but, on the other hand, if the pitch of the damper slots is any exact multiple or

submultiple of the pitch of the stator slots, the tooth-ripples may be greatly exaggerated.

The bars are either brazed or electrically welded to the end rings; and the latter are connected together between poles by bolted and sweated joints. The stress in the end rings is very considerable, and therefore the bars should project beyond the ends of the poles as little as possible. In high-speed machines, the end rings may need to be complete rings, cast in one piece, and possibly of manganese bronze. Even then the stress in the damper rings may set a limit to the possible speed of single-phase water-wheel alternators.

CHAPTER V

Design and Construction of Transformers

1. The maximum voltage for which rotating machinery can be wound is only suitable for economical transmission of power over a limited distance. This limitation necessitates the use of transformers to step up the voltage generated by the alternator to a value suitable for economical distribution, and to step down the voltage, at the end of the transmission line, to a value suitable for industrial purposes.

A transformer consists essentially of two electric conducting circuits (the primary and secondary windings) insulated from one another and interlinked

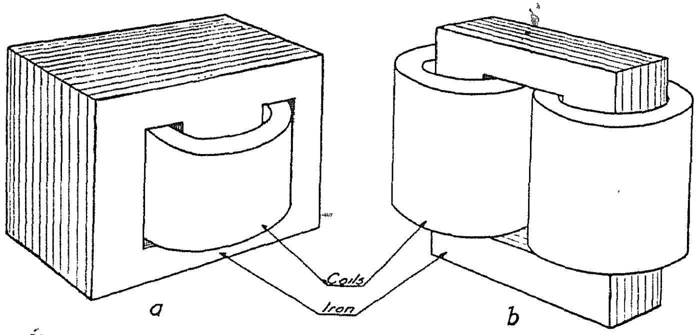


Fig. 1.—*a*, Core Type Transformer. *b*, Shell Type Transformer

with a common magnetic circuit (the core) so as to be mutually inductive. The common arrangements of the core and windings divide commercial transformers into two types:

(*a*) Core type,
(*b*) Shell type.

These types are represented in fig. 1, from which it will be observed that, whereas in the core type the windings very largely surround the magnetic circuit, in the shell type the magnetic circuit surrounds the windings.

Magnetic Circuit.—In both types the magnetic circuit is built up of laminations of high grade silicon iron, usually from ·014 to ·02 in. thick. The iron is generally papered on one side to ensure that the laminations are insulated one from another, thus preventing excessive eddy currents in the iron. Fig. 2 illustrates the magnetic circuit of a core type transformer,

with the top yoke removed in readiness for assembling the coils on the three vertical limbs. The bottom horizontal yoke laminations are secured by insulated bolts to channel iron supports, which form the base of the finished transformer. The vertical laminations are similarly held by stiffening plates. The top horizontal yoke laminations are placed in position when the coils are assembled. There may be butt joints between the horizontal and the vertical laminations, or they may be interleaved one with the other.

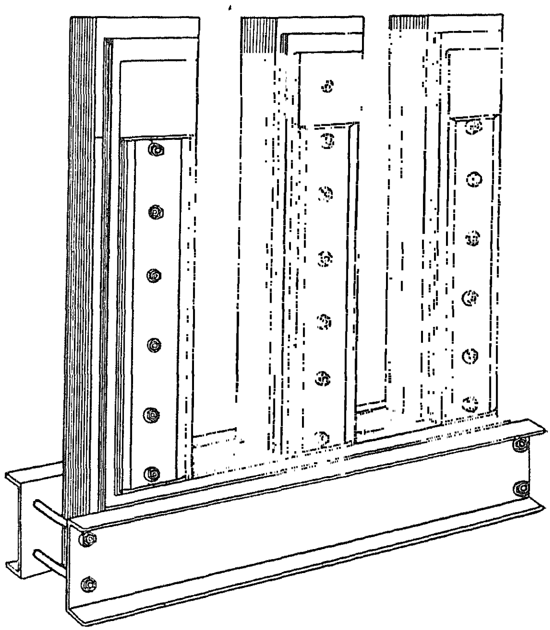


Fig. 2.—Magnetic Circuit of Core Type Transformer (top yoke removed)

The assembly of the magnetic circuit of a shell type transformer is illustrated in fig. 3. Some of the iron has been placed in position around the finished coils and insulation. The laminations are finally clamped in position by heavy end frames, which are securely bolted together.

Windings and Insulation.—The design of the primary and secondary windings of a transformer, and their efficient insulation, require particular care if there is to be immunity from breakdown, and if ample provision is to be made to conduct away the heat generated in the innermost coils.

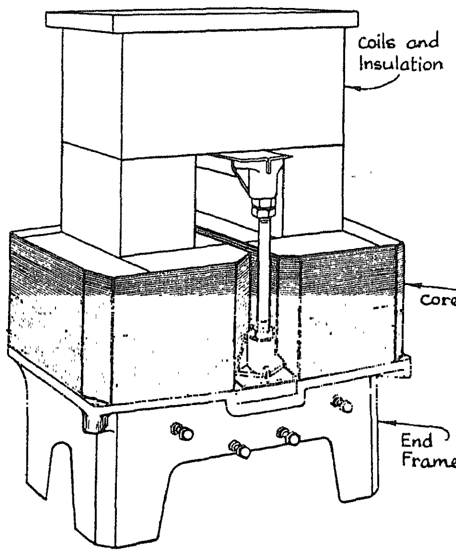


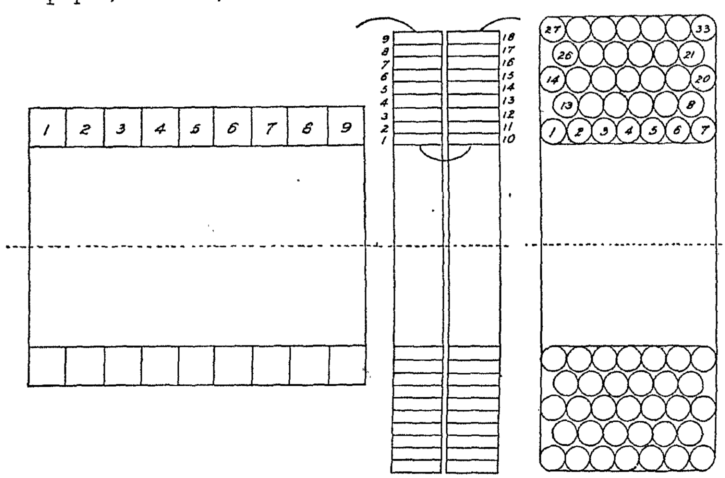
Fig. 3.—Shell Type Transformer with Magnetic Circuit partially assembled

In the core type construction, the coils are generally circular, and in the simplest case consist of a single layer of turns wound in cylindrical form. Each turn, if the winding is to be suitable for carrying a heavy current, may consist of several conductors connected in parallel. It is usual for the conductors to be cotton covered, and spacing

strips to be wound in between the adjacent turns. This type of winding is commonly used for low-tension coils where the high-tension and low-tension windings are arranged concentrically.

For high-tension windings, where there are a large number of turns, it becomes necessary to adopt a different type of coil. There are two types in common use, one used where conductors are of a greater area than approximately ·01 sq. in., and the other for conductors of a smaller area.

In the former case a ribbon-shaped conduct is preferable. Fig. 4 *b* illustrates the winding of this type of coil, the turns being wound one on another in a radial direction, and insulated from one another by using cotton-covered wire and fullerboard spacing strips, or by wrapping bare wire with paper, cambric, or other similar material.



a, Single Layer Cylindrical Coil *b*, Pancake Coils *c* Multilayer Coil

Fig. 4.—Types of Coils. Numbers represent order of winding the turns

Coils are assembled together by joining the inside turn of one coil to the inside turn of the adjacent coil in one direction, and the outside turn to the outside turn of the next coil in the other direction. In order to avoid the inside joint, two of the coils may be wound from one length of wire by winding the turns in the order indicated in fig. 4 *b*. The correct rotation is obtained by winding the first coil in one direction and the second coil in the reverse direction.

For the second type of high-tension coil conductors of circular section are preferable. These coils are wound as illustrated in fig. 4 *c*. Cotton-covered wire is usually used, the cotton acting as insulation between adjacent turns of the same layer. As a considerable voltage may exist between the end turns of adjacent layers, special care must be taken with the insulation at these points.

Coils for shell type transformers are wound in the same manner as the first type of high-tension coils described above. They are, however, usually of rectangular shape instead of circular, and, on account of the greater

length of wire used per coil, it is not practicable to wind two coils without an inside joint between them.

Coil Arrangement.—Core type transformers usually have the windings assembled in one of the two arrangements illustrated in fig. 5.

In fig. 5 *a* the low-tension winding consists of a single layer coil of the cylindrical type, which is generally placed adjacent to the core. The high-tension winding may consist of a number of coils of either of the types already described. The windings are separated by as large a space as practicable, so as to form an ample cooling duct. In this duct there is also an insulating cylinder of sufficient thickness to withstand the electrical stress set up

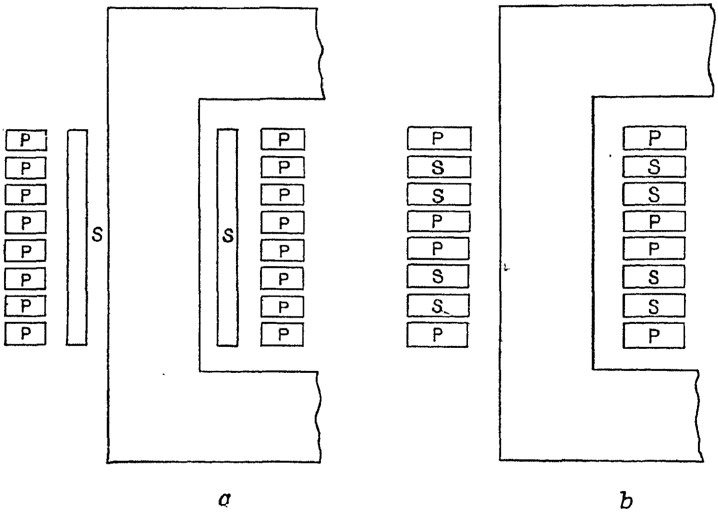


Fig. 5.—Arrangement of Coils

P, Primary winding. S, Secondary winding.

between the two windings. It is usual to provide ducts between adjacent high-tension coils, further to facilitate the circulation of the cooling medium.

In the second method the high-tension and low-tension coils, instead of being concentric, are interleaved in sandwich fashion, as shown in fig. 5 *b*. As the coils are usually assembled in a horizontal plane, the cooling ducts lie at right angles to the natural flow of the cooling fluid.

Shell type transformers have the coils and insulation assembled complete, and the iron built up round them. The coils are interleaved, as in the second method described for core type transformers, but, as they are usually assembled in the vertical plane, the disadvantage with regard to the cooling does not arise. Fig. 6 shows a set of coils in the course of assembly. The features to be noted are the narrow width of the individual coils, and the method of separating adjacent coils by wave-shaped strips in such a manner that every individual turn is supported.

Coil Bracing.—Under short circuit conditions, large forces are set up between the two windings which may reach a very high value. It will be

realized, therefore, that adequate bracing of the coils is of considerable importance. This is particularly the case where the coil arrangement is such that there is a possibility of shrinkage of the insulation, for, unless the supports can be adjusted to take up any shrinkage, there may be movement of the coils, resulting in damage to the insulation, and causing an electrical breakdown.

With shell type construction the insulation is not liable to shrinkage, because it has not the weight of the copper bearing upon it. The coil bracing, therefore, need only be adjustable to ensure that the windings are securely clamped in the first case, and no adjustment should be neces-

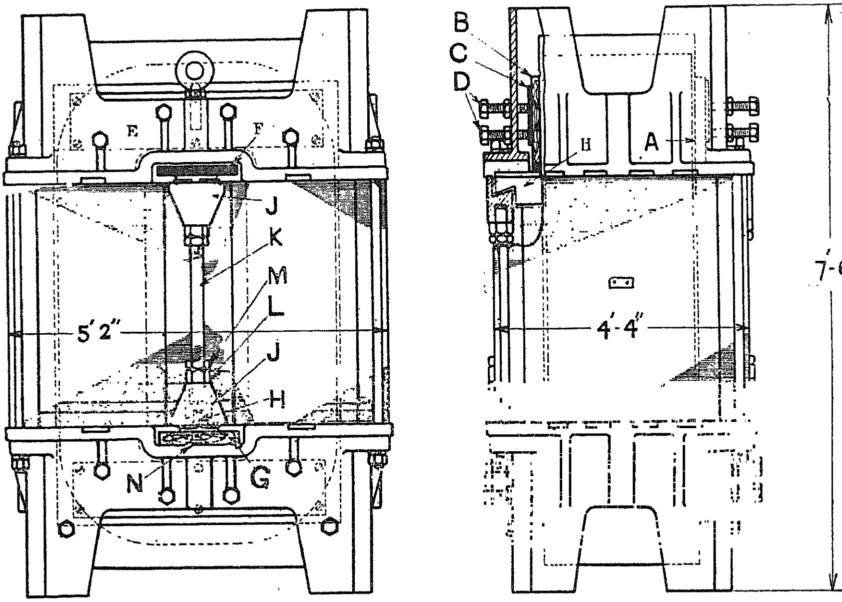


Fig. 7.—Coil Bracing Arrangements on a Shell Type Transformer

A, Coil heads. B, Wood packing. C, Steel plate. D, Adjustable bolts. E, End frame. F, Wood packing. G, Wood packing base. H, Angle-iron supports. J, Supporting bracket. K, Adjusting supporting bolt. L, Adjusting nut. M, Lock nut.

sary after the transformer has been in service. Fig. 7 shows the usual arrangements made for supporting the coils on this type of transformer.

The conditions existing in core type transformers are rather different. The coils are usually stacked one on top of another so that each coil has to support the weight of the coils above it. Under the continual heating and cooling, which occurs throughout the normal working of a transformer, the insulating material used in the windings is very liable to contract, with the result that, after some months in service, the coils will not be clamped tightly unless the supports have been adjusted to take up the shrinkage. One large manufacturer claims that, by special treatment of the coils and by great care being taken in the manufacturing process to see that the coils are thoroughly shrunk before leaving the factory, no shrinkage occurs in

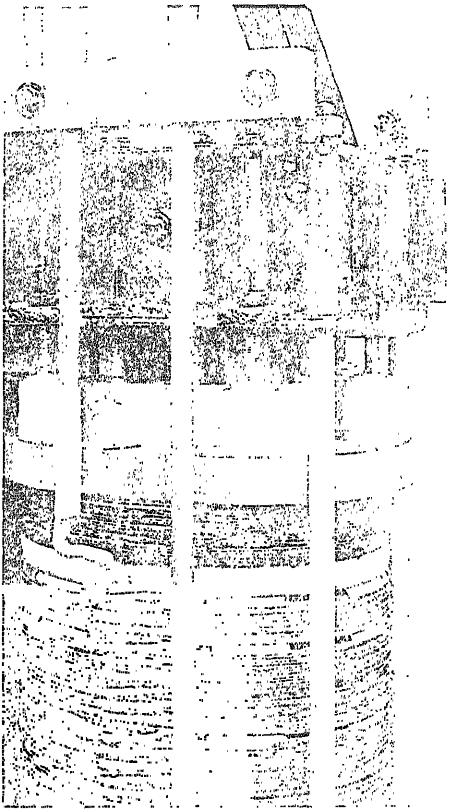


Fig. 10.—Core Type Transformer Coil Supports (Metro.-Vickers)

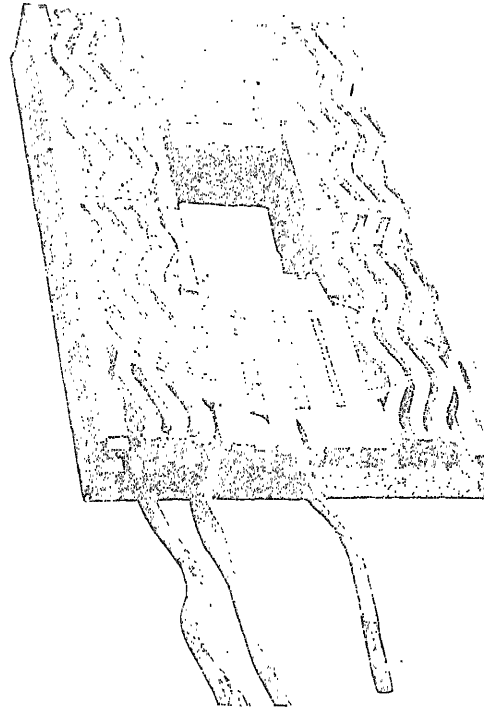


Fig. 6.—Shell Type Coils being assembled

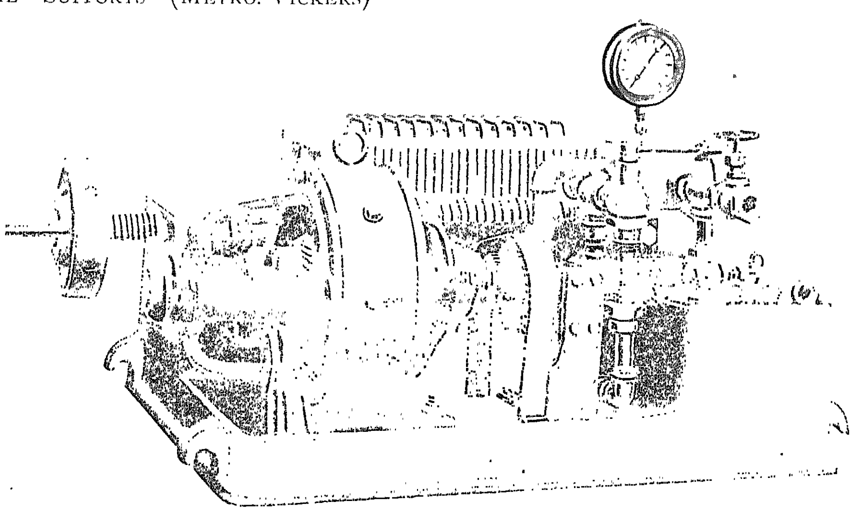


Fig. 8

the windings of their core type transformers. In this particular case the coils are supported by being tightly clamped between the channel irons used to support the top- and bottom-yoke punchings. It is questionable, however, whether windings on large and high-voltage transformers can be so thoroughly shrunk during manufacture as to prevent any further shrinkage in service.

Fig. 8 shows another arrangement of coil bracing. The windings are clamped between two end castings in such a manner that the coils are completely assembled before being placed on the limb. Springs are threaded on the tie bolts and take up any shrinkage which may occur. A further arrangement is illustrated in fig. 9. In this case the coils are clamped between the top and bottom channel irons, and springs are placed between metal plates in the centre of the windings. In both this and the previous case, movement of the coils may take place under short circuit.

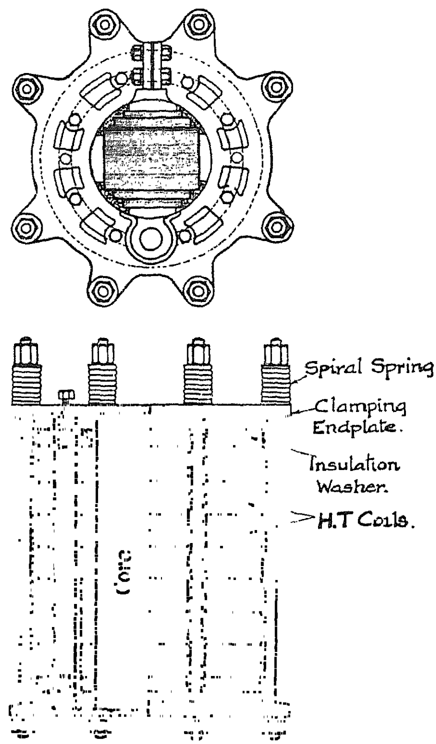


Fig. 8.—Spring Coil Supports for automatically taking up Shrinkage of Windings on Core Type Transformers (Brown, Boveri, & Co.)

Another alternative arrangement which overcomes this difficulty is illustrated in fig. 10. In this case springs are also used, but are placed between a metal ring fitted on the top of the coils and the top supporting channel irons. The springs are enclosed in an oil-filled dashpot, so that the pressure exerted by the springs tends to open the dashpots and takes up any shrinkage, and, at the same time, draws oil into the dashpot through a small hole provided for this purpose. In the event of abnormal forces being set up, which tend to compress the springs, it will only be possible to do this at the rate at which the oil can be forced out of the dashpot through the small hole. As this will only be at a very small rate, no appreciable movement will take place before the normal conditions are restored.

The forces set up in a radial direction are not sufficiently great to necessitate external bracing, except in very large transformers. It is usual, however, to space the coils from the iron and from one another by hardwood wedges.

2. Cooling Systems.—Transformers of small outputs rely on the surfaces of the coils and iron to dissipate the heat generated in the respective

parts. Such dry type natural-cooled transformers are not generally manufactured for outputs greater than 100 k.v.a.

On larger size units a number of alternative methods of cooling are in use, and are usually designated as follows:

(*a*) Dry air blast.
(*b*) Oil-immersed, natural-cooled.
(*c*) Oil-immersed, air blast.
(*d*) Oil-immersed, water-cooled.
(*e*) Oil-immersed, forced-cooled.

(*a*) *Dry air blast.*—In this method the heat is dissipated by blowing air through ducts provided in the coils and core. Satisfactory cooling is

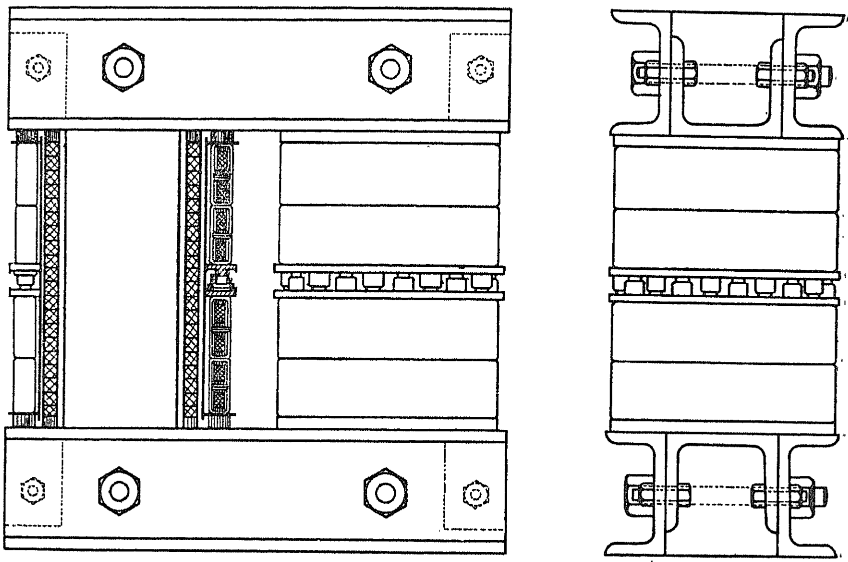


Fig. 9.—Spring Coil Supports for automatically taking up Shrinkage of Windings (Ferranti, Ltd.)

obtained by this means with carefully designed transformers, but there is always a liability of hot spots in the windings. This method is limited to comparatively low-voltage transformers, on account of insulation difficulties resulting largely from the danger of moisture being present in the air. For use in a climate such as exists in Great Britain this type is not recommended for pressures above 11,000 volts.

(*b*) *Oil-immersed, natural-cooled.*—This class covers the majority of transformers from 100 to 2000 k.v.a. capacity, and in recent years many much larger units have been built. Transformers of this type have the coils and core immersed in oil, to which the heat generated is transferred by conduction.

The oil is cooled by making the tank surface sufficiently large to dissipate the heat by natural radiation. There are several methods of obtaining the required surface, of which the most common is by the use of cooling

tubes welded into the sides of the tank, as shown in fig. 11. Owing to the expansion of the oil with increasing temperature convection currents are set up, which flow towards the surface and return through the cooling tubes to the bottom of the tank. Tanks of this type may be made to dissipate about 50 kw., which corresponds to a 4000 k.v.a., three-phase, 50 cycle, 33,000 volt transformer.

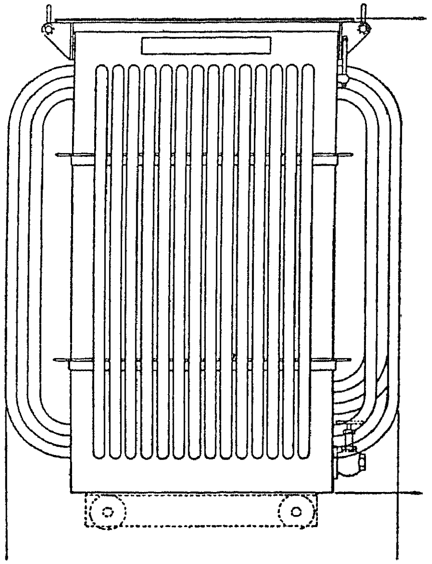


Fig. 11.—Boiler-iron Tank fitted with External Cooling Tubes

Another method which has been adopted largely in America is illustrated in fig. 12. Radiators which are separately constructed are bolted on to the tank sides. By this means a much larger surface may be obtained, and transformers of 10,000 k.v.a. rating have been cooled in this manner.

(*c*) *Oil-immersed, air blast.*—An alternative method of keeping the temperature rise of the oil within the required limits is to direct a blast of air on to the walls of the tank in which it is contained. This method is not generally used, as large transformers are more often cooled by one of the following methods.

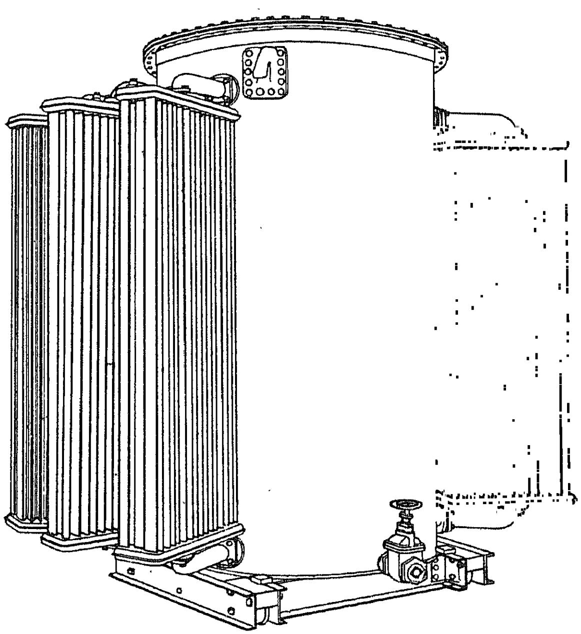


Fig. 12.—Tank fitted with Radiators

(*d*) *Oil-immersed, water-cooled.*—In this type the oil is kept cool by transferring the heat to water, which flows through a coil of metal piping mounted in the upper part of the tank where the oil is hottest. This method is suitable for large units, and is of particular interest where floor space is limited.

(*e*) *Oil-immersed, forced-cooled.*—A further means of extracting the heat from the oil is by the use of an external cooler, through which the hot oil is circulated by a pump.

Fig. 13 illustrates the general layout of a three-phase bank of single-phase units which are cooled in this manner.

3. General Construction.—The general construction of a three-phase core type transformer is illustrated in fig. 14, which represents a 3000 k.v.a., three-phase, 50 period, 5000/52,000 volt, star/star connected, oil-insulated, water-cooled transformer manufactured by Messrs. Brown, Boveri, & Co. The windings on each phase are arranged concentrically, and the low-tension winding is divided into two concentric coils, one being next to the core and the other on the outside. The high-tension winding is situated in between the two low-tension coils. The coils are braced by the method already described. From the plan view it will be seen that the tank is shaped so as to provide ample room for the high-tension terminals and at the same time to avoid the increase in oil quantity, which would arise if the tank was made symmetrical.

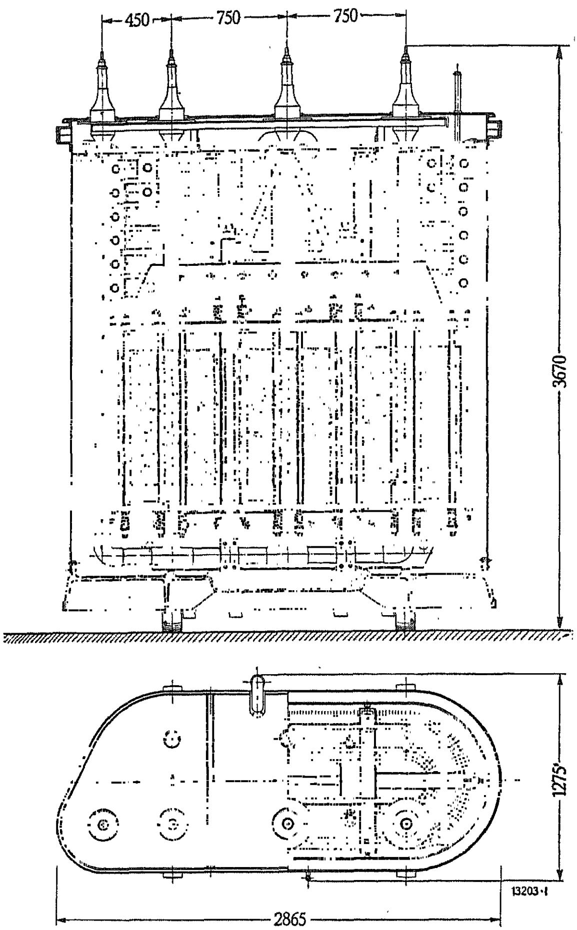


Fig. 14.—Three-phase Oil-immersed Transformer. 3000 k.v.a., 5000/52,000 volts, 50 cycles (Brown, Boveri, & Co.)

The tank is made of boiler plate mounted on a cast-iron base, which is provided with suitable lugs for the attachment of ropes or chains by which the complete transformer, filled with oil, may be lifted. The base is also designed so as to facilitate the correct spacing of the core and winding from the tank sides, to prevent any movement during transport and erection.

The transformer is cooled by means of the circulation of water through the cooling tube, fixed immediately under the surface of the coil, which is made of galvanized-iron tubing with ribs placed at short intervals along its length to increase the surface. In the event of any interruption in the flow

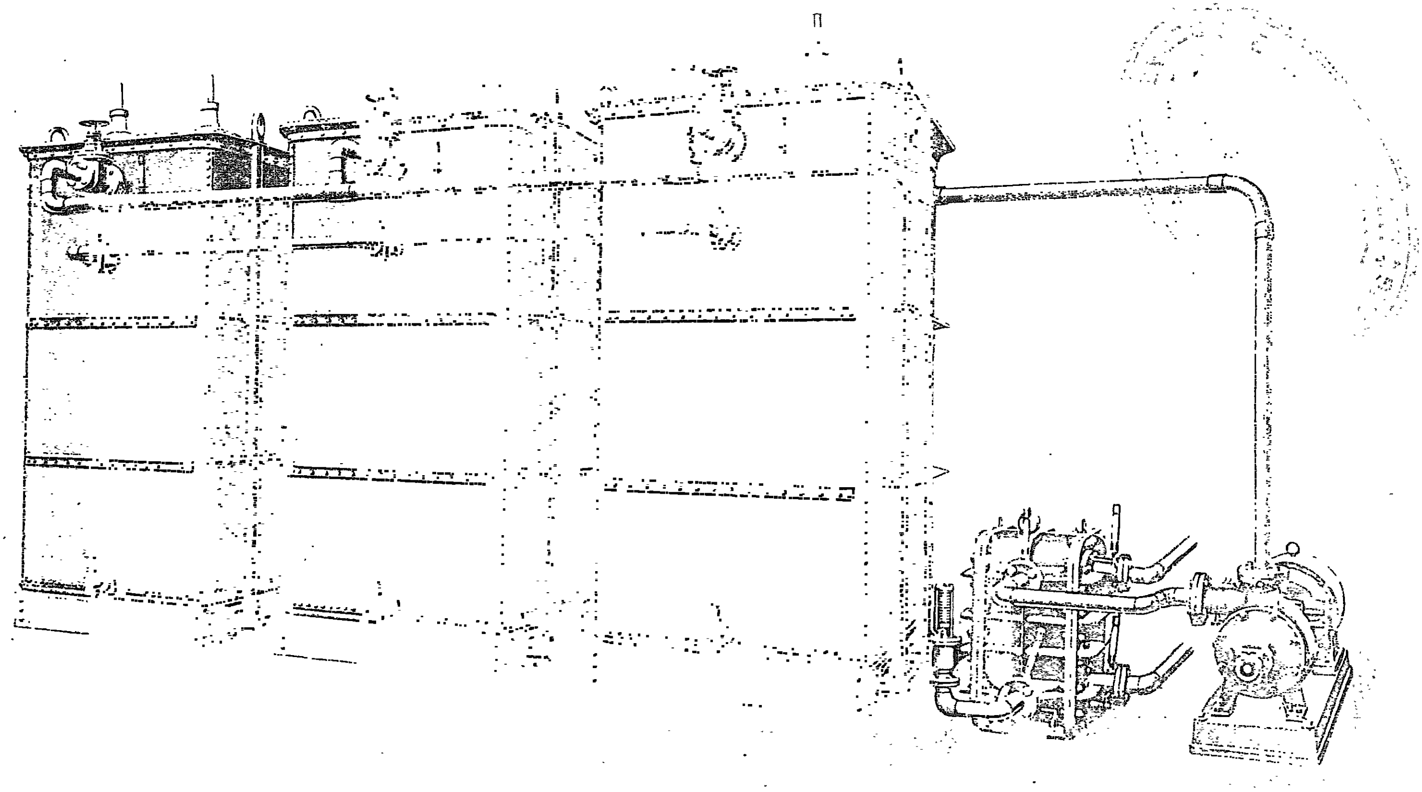


Fig. 13.—General Arrangement of Three Single-phase Oil-immersed Forced-cooled Transformers

of the cooling water, an automatic device in the water-pipe causes an electric alarm bell to ring.

Fig. 15 illustrates a typical single-phase shell type transformer manufactured by the Metropolitan-Vickers Electrical Company. It is one of three transformers which form a 9000 k.v.a., three-phase, 50 period,

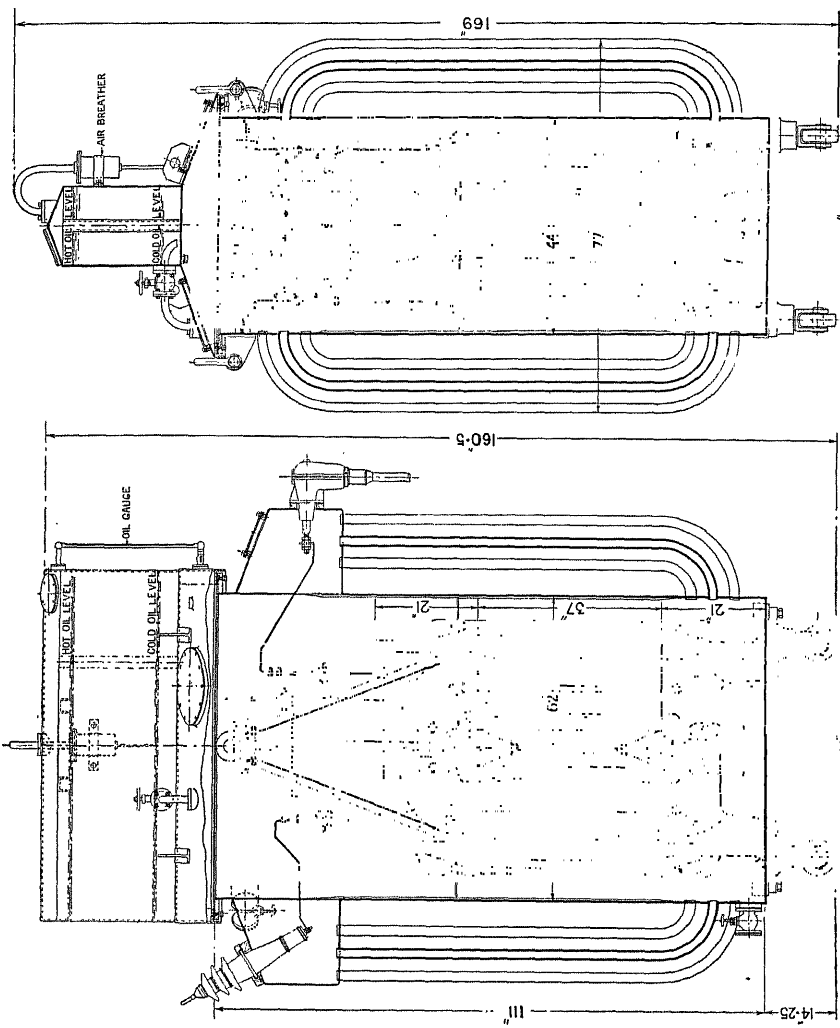


Fig. 15.—3000 k.v.a. Single-phase Shell Type Transformer. 33,000/6000 volts, 50 cycles (Metropolitan-Vickers)

33,000/6000 volt, delta/star connected, oil-immersed, natural-cooled group. One of the most interesting features is the weatherproofing arrangement, which enables the transformer to be installed out of doors. Such an arrangement is becoming common practice in this country, and has been used extensively in America for some time.

In such cases the design must be such that there is no possibility of any moisture entering into the tank under any atmospheric conditions which

are likely to arise. In this instance a sloping cover is used, which overlaps the tank side, and which is bolted in position from the under side, thus preventing any accumulation of water, and also protecting the joint. All joints are made airtight by the use of suitable packing material. An oil-expansion chamber, forming an integral part of the cover, is provided, which allows the main tank to be completely filled with cold oil, and provides space into which the oil may expand when the transformer heats up under load. With such an arrangement the oil comes in contact only with

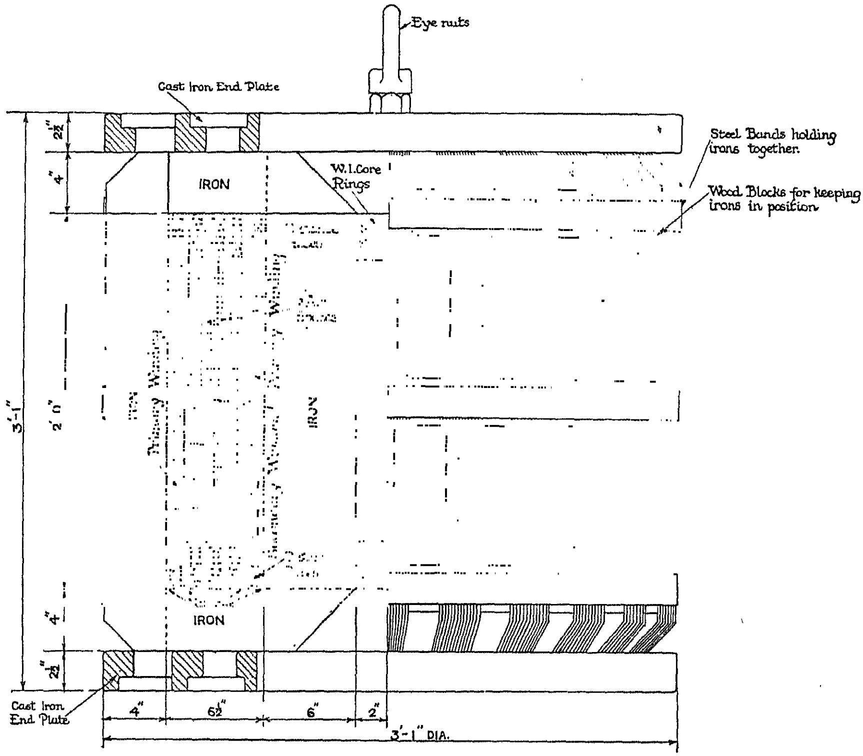


Fig. 16.—General Arrangement of "Berry" Type Transformer

the limited volume of air contained in the expansion chamber, and so reduces the tendency to oxidation of the oil. If suitable breathing apparatus is provided, which usually consists of a chamber containing calcium chloride, the air entering the conservator may be dried, and the risk of moisture being absorbed in the oil made negligible.

The terminal arrangement is a further interesting feature. On the high-tension side the line connections are led into the tank through weatherproof porcelain insulators, while on the low-tension side single-pole sealing bells are provided, which are suitable for single-core, lead-covered cable. By mounting these terminals as shown, the transformer may be removed from the tank without disturbing the high-tension or low-tension line leads.

Fig. 16 illustrates the general arrangement of the construction used by the British Electric Transformer Company. The coils are circular and similar to those usually used in core type construction. The iron circuit encloses the coils, as in the shell type construction, but is distributed symmetrically round them, with the horizontal punchings arranged radially to the coils' axes. The iron is grouped into a number of packets with spaces between them, thus providing a large surface for the dissipation of the heat.

The illustration shows the details of a 500 k.v.a., single-phase, oil-immersed, natural-cooled transformer, removed from its tank.

In addition to the points mentioned in reference to figs. 14, 15, 16, the following are of general interest.

Tappings.—Tappings may be brought out from the windings to give several voltages above and below the normal voltage. Such tappings are of special use where a transformer may be installed at any one of numerous sub-stations situated at different distances from the generating station. Under such conditions, as the voltage at the sub-stations will differ, when installing a transformer, the appropriate tapping for the particular voltage may be utilized. The number of tappings should be kept as low as possible, as the introduction of each additional one introduces a possible source of breakdown. It is usually found that tappings to give plus and minus 5 per cent of the normal voltage are sufficient for general purposes.

Terminal Bushings.—The terminal bushings generally used on transformers are exactly similar to those used on switchgear, and call for no further comment beyond the description given in Chapter X. Transformers for use on low-pressure systems (approximately up to 11,000 volts) may have the bushings mounted on the side of the tank, but on high-voltage transformers, owing to the length on the inside, the bushings are usually mounted on the tank cover.

Insulation of End Turns.—The end turns of the windings adjacent to the line terminals, under certain conditions, may be subjected to an abnormal voltage stress, which necessitates special care being taken in the design of the windings to reinforce the insulation at these points. Such conditions may arise due to switching, or may be caused by atmospheric disturbances, but in all cases the time during which the stress continues is very short. Opinions differ as to the extent to which the windings should be reinforced, but, if for line pressures up to 66,000 volts 1 per cent of the turns are insulated to withstand line voltage momentarily, and the insulation is graded down to normal within the next 3 per cent of the turns, no trouble should be experienced.

PERFORMANCE

4. Temperature Rise.—It is usual for the temperature rise of a transformer to be guaranteed not to exceed a specified figure after a full load test of sufficient length of time for the temperature to have become constant. The length of time required for this condition to be attained varies over

wide limits. It may be as short as four hours, in the case of a small transformer, or as long as sixteen hours, in the case of a large oil-immersed natural-cooled transformer.

Fig. 17 shows typical curves for transformers of various sizes.

The temperature rise may be measured in three ways:—

(*a*) By thermometer.
(*b*) By the increase of resistance of the windings.
(*c*) By thermo-couples or resistance elements embedded in the core or windings.

Referring particularly to oil-immersed units, the temperature of the hottest part of the oil is measured by method (*a*). This method alone

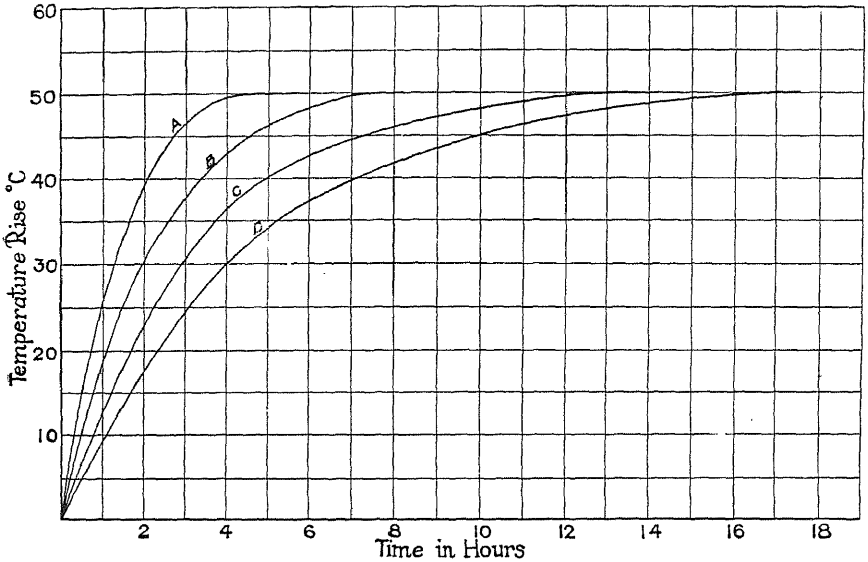


Fig. 17.—Typical Temperature Rise Curves

A, 2000 k.v.a. oil-immersed forced-cooled transformer. B, 50 k.v.a. oil-immersed natural-cooled transformer. C, 500 k.v.a. oil-immersed natural-cooled transformer. D, 2000 k.v.a. oil-immersed natural-cooled transformer.

does not necessarily give a true indication of the temperature rise, as a transformer may be designed with the copper and iron loaded very highly and the resulting large losses dissipated by the use of a large tank. In such a case the internal temperature of the windings and core will be considerably in excess of the temperature measured in the oil. A similar result will be obtained where the current density in the copper and induction density in the iron are of quite average values, if, in the design of the windings and the core, sufficient oil ducts have not been provided to enable the heat to be conducted away from the internal parts. This point is of very great importance in large units.

It will readily be seen from the above considerations that method (*b*)

is a more preferable means of determining that the temperature rise is not excessive, though in this case, as it is usually only possible to measure the resistance of the whole of the primary or secondary winding, an average result only is obtained, and the temperature rise of a portion of the winding may be much higher than the average.

For these reasons it is becoming common practice to insert a resistance element in the interior of the coils and iron during manufacture, so that the temperature rise may be measured where it is likely to be highest. With this arrangement some provision must be made to ensure that the indicator is not at a dangerous potential above earth.

The limiting temperature permissible depends on the nature of the insulating material used, and which usually comes under the classification of " cotton, paper, and similar materials when impregnated ".

The following table gives the maximum temperature rise allowed under various standard rules:

Country.	Authority.	Temperature Rise.		Air Temperature Basis.	Maximum Temperature in Oil by Thermometer.
		Oil (by Thermometer).	Windings (by Resist.).		
Great Britain	B. E. S. A. Report 72 (1917)	50° C.	55° C.	40° C.	90° C.
United States of America	Standardization Rules American I. E. E. (1921)	—	55° C.	40° C.	90° C.
France	Union des Syndicates d'Electricité (1913)	55° C.	60° C.	35° C.	—
Germany	V. D. E. Normalien (1921)	60° C.	70° C.	35° C.	95° C.

5. Losses.—The losses in a transformer are divided into two classes:

(*a*) Iron loss.
(*b*) Copper loss.

(*a*) *Iron loss.*—Iron loss includes all losses which occur in the magnetic circuit, which are due to two causes (*a*) hysteresis and (*b*) eddy currents. The highest quality silicon iron has an average " figure of loss " of ·7 to ·8 watts per pound, at an induction density of 10,000 lines per square centimetre, and a frequency of fifty cycles per second. The loss varies approximately as the square of the induction and approximately directly as the frequency.

(*b*) *Copper loss.*—The copper loss is made up of the I^2R loss of the primary and secondary windings and the eddy current loss in the copper due to the magnetic leakage flux set up between the two windings. In addition any eddy current losses in the constructional parts are also comprised in the measured copper loss.

Efficiency.—The efficiency of a transformer is higher than that of

any other electrical machine, and in large size units may be as high as 99 per cent.

Typical efficiency curves for small and large transformers are shown in fig. 18.

It will be noticed that the curves for 25 and 50 cycle transformers are of different shape, the former showing higher efficiencies at low loads. This is on account of the different ratio of iron loss to copper loss in the two cases. Where a high efficiency is required at light loads, the iron loss must be as small as possible in comparison to the copper loss.

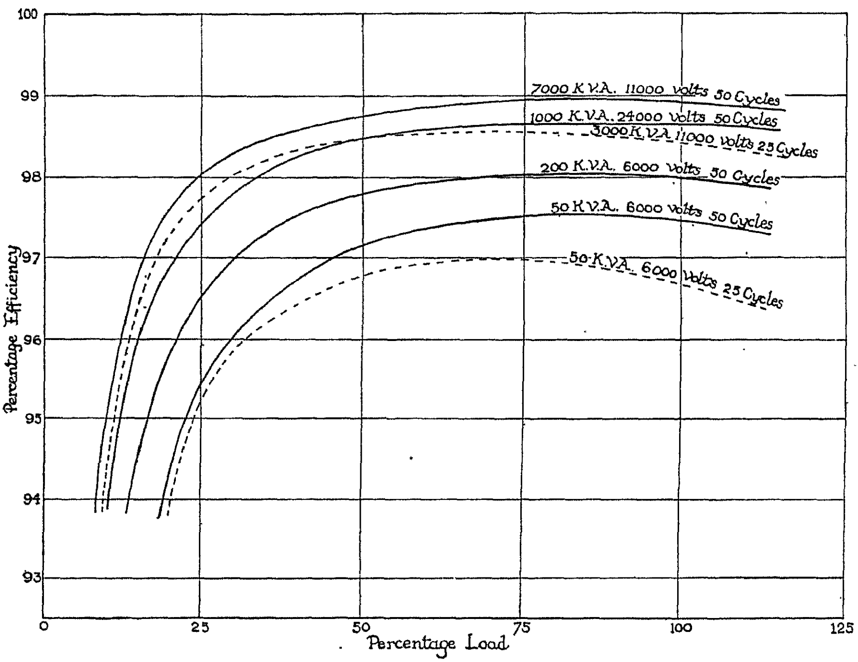


Fig. 18.—Typical Efficiency Curves

6. Reactance.—The reactance voltage of a transformer is a voltage which is induced due to leakage flux set up by the ampere turns of the primary and secondary windings, and which is therefore in quadrature with the currents in the windings. It will be evident, if the load is of other than unity power factor, that the reactance voltage will have a component in phase with the primary and secondary voltages, and will add or subtract from them. If the power factor is leading, the result will be a rise in secondary voltage, and if the power factor is lagging a drop in secondary voltage. The latter case is by far the more common, and hence, in small distributing transformers, where it is necessary that the voltage is maintained as constant as possible, the reactance is usually kept of low value by suitable grouping of the primary and secondary windings.

A more important function of the reactance is its effect on the value of

the current which will flow if normal voltage is maintained across the primary winding and the secondary winding short circuited. Under these conditions the current will be equal to the full load current multiplied by 100 and divided by the percentage reactance at full load. For example, a transformer, having 5 per cent reactance at full load, will have a maximum short-circuit current of 20 times full-load current. It will be seen that the short-circuit current varies inversely as the reactance. The importance of the limitation of the maximum short-circuit current of large power transformers will be realized, when it is observed that the forces exerted are proportional to the square of the current and therefore inversely as the square of the percentage reactance.

The size of unit and its position on the system determines the value of the reactance which is to be recommended for any particular unit. Transformers installed in a power station of large generator capacity should have a high reactance. In the case of a 20,000 k.v.a. unit stepping up the generated voltage to the transmitted voltage, and with no external protective reactance installed, the full-load reactance may be as high as 15 per cent, whilst in a 100 k.v.a. distributing transformer, installed at the end of a long feeder, 3 to 4 per cent may be considered ample.

7. Regulation.—The regulation of a transformer is the drop in secondary voltage between no load and full load, and is usually expressed as a percentage of the no load voltage.

This drop is made up of two components: (*a*) the resistance drop in the windings, which is in phase with the current, and (*b*) the reactance drop, which is in quadrature with the current.

It will be seen then, that, if the current is in phase with the voltage (i.e. unity power factor load), the resistance drop will be in phase with the voltage and the reactance drop will be in quadrature, and therefore have no component in phase with the voltage.* Under this condition the regulation will be equal to the resistance drop.

Similarly, if the current lags 90° behind the voltage (zero power factor), the regulation will be equal to the reactance drop.

At intermediate power factors the regulation will be made up of components of each of these drops, and its value may be obtained from the following formula:

$$\begin{aligned}&\%\text{ regulation of any power factor}\\&\quad= \%\text{ resistance drop} \times \text{PF} + \%\text{ reactance drop} \times \sqrt{1 - \text{PF}^2}.\end{aligned}$$

8. Connections.—Transformers for use on three-phase circuits may have the primary and secondary windings connected in one of several ways. It is usual, however, for the connections to be a combination of the star and delta arrangements.

Owing to the flux density in an iron core not being a linear function of

* This statement is only approximately true, and applies particularly to transformers of low reactance.

the magnetizing current, there must be a third harmonic component in the magnetizing current in order to obtain a sine wave of flux. If, for any reason, this third harmonic component cannot flow, then there will be a third harmonic present in the flux wave and consequently in the induced voltage wave.

It is an inherent quality of the star connection that a third harmonic current cannot flow from the lines, unless there is a return circuit available through the neutral point. As a result, unless the required harmonic magnetizing current is supplied from some other source, there will be a third harmonic present in the voltage between each line and neutral, but not in the voltage between lines. For this reason, it is not usual to use transformers with both the primary and secondary windings connected in star, especially in the case of three-phase shell type units or of a bank of transformers consisting of three single-phase units. In such cases, if the neutral point is earthed, there is the possibility of a third harmonic capacity current flowing to earth and causing telephone disturbances in the neighbouring districts. A further disadvantage is that, if the load is not equal on all phases, there will be a distortion of voltage between each phase and neutral, which in extreme cases may cause heating up of the core of one of the phases.

The delta connection overcomes the difficulty of the supply of the necessary third harmonic magnetizing current, for, although it still cannot be supplied from the lines, it will be supplied by the necessary current flowing round the delta connection. This connection is also suitable for unsymmetrical loading. For these reasons, it is usual to connect one winding of the transformer in delta.

The most common combination is for the primary winding to be connected in delta and the secondary winding to be connected in star, so that the neutral point of the secondary winding may be earthed.

Where three single-phase transformers are used as a three-phase bank, both the primary and secondary windings are usually connected in delta, if it is not desired to earth either system at the neutral point of the transformer windings. Under such circumstances this connection has the advantage, in case of breakdown of one of the three single-phase units, that the remaining two may be connected in open delta, and will supply a load of 58 per cent of the normal full load of the bank.

Small distributing transformers are sometimes connected in star/zig-zag instead of delta/star, on account of the larger current obtained in the primary winding, enabling more robust coils to be wound. This connection has similar characteristics to the delta-star connection as far as balancing is concerned, and no third harmonic exists in the phase to neutral, or phase to phase voltages of the zigzag windings.

9. Parallel Operation.—Where two or more transformers have to run with their primary and secondary windings respectively connected in parallel, the following conditions must be fulfilled if satisfactory operation is to be obtained:—

(*a*) There must be the same angular displacement between the primary and secondary voltages.
(*b*) They must have exactly the same ratio of primary and secondary voltages at no load.
(*c*) They must have the same voltage regulation at all power factors.

(*a*) This condition arises particularly in the case of three-phase transformers, as different combinations of connections give different angular displacement between primary and secondary voltage. The following table shows which of the more common connections give the same angular displacement and are therefore suitable for transformers which have to operate in parallel.

	Y/Y	Δ/Δ	Δ/Y	Y/Δ	Y/Z	Z/Y
Y Y	*yes*					
Δ Δ	*yes*	*yes*				
Δ Y	*no*	*no*	*yes*			
Y Δ	*no*	*no*	*yes*	*yes*		
Y Z	*no*	*no*	*yes*	*yes*	*yes*	
Z Y	*no*	*no*	*yes*	*yes*	*yes*	*yes*

(*b*) Unless each unit has the same voltage ratio at no load, as soon as the two secondary windings are connected in parallel, there will be a circulating current flowing round the two secondary windings. The amount of current which the windings will carry without undue heating is fixed; therefore, if there is a circulating current in the windings at no load, the amount of load current which they are capable of carrying in addition will be less than the sum of the individual full-load currents of each unit. When the transformers are actually on load, the effect will be that the transformer with the higher secondary voltage will take more than its share of the load.

(*c*) This condition is necessary in order that transformers, which have the same ratio at no load, may maintain a similar ratio under all load conditions. From the previous discussion on the regulation of a transformer it will be seen that, to meet this condition exactly, the resistance and reactance drops of the various transformers must be identical. Although this is true for perfect parallel operation, satisfactory service may be obtained if the values of $\sqrt{\text{resistance drop}^2 + \text{reactance drop}^2}$ (known as the impedance drop) for the various transformers are equal.

10. Choice of Type.—The chief points for consideration in deciding what type of transformer to install under any particular circumstances may be divided under three headings as follows:

(*a*) Type of cooling.
(*b*) Multiphase transformers or groups of single-phase units.
(*c*) Core type or shell type units

(*a*) *Type of Cooling*.—This is the most important point to be settled, and is very largely governed by the size of the unit under consideration, and upon the situation in which it is to be installed. If the site is such that there is not an ample supply of water available for cooling purposes the choice of type is limited, except in very small units, to oil-immersed, natural-cooled transformers or to air-blast transformers. As pointed out under the description of air-blast transformers, these are only suitable for comparatively low voltages, so that, in most cases, it becomes essential to install transformers of the oil-immersed, natural-cooled type. This same type will naturally be chosen for isolated sub-stations where continual attendance is not available.

Where cooling water can be obtained without difficulty it will be found, on considerations of first cost, floor space, and head room, that oil-immersed, water-cooled transformers can be installed with advantage for capacities above the following:

2500 k.v.a., three-phase, 50 periods,
1700 k.v.a., three-phase, 25 periods,
1500 k.v.a., single-phase, 50 periods,
1000 k.v.a., single-phase, 25 periods.

This method of cooling has been adopted for very large transformers, particularly in America, but there are several advantages in using oil-immersed, forced-cooled transformers for very large outputs. Although more floor space is required, on account of the auxiliary apparatus necessary, there is usually a saving in height. A better circulation of oil is obtained, resulting in more uniform cooling of the windings, and a further advantage is that by fitting a suitable back-pressure valve to the cooler oil outlet, the possibility of leakage of water into the oil is reduced to a minimum. For these reasons, therefore, oil-immersed, force-cooled transformers are recommended above the following limits:

5000 k.v.a., three-phase, 50 periods,
3500 k.v.a., three-phase, 25 periods,
3500 k.v.a., single-phase, 50 periods,
2500 k.v.a., single-phase, 25 periods.

(*b*) *Single-phase versus Three-phase*.—In deciding between these two alternatives, the main considerations are capital cost (including the cost of spare parts) and floor space. It may be assumed that both types are equally reliable, and that in each case spare parts are to be stocked to ensure a continuity of supply. In certain cases the question of weight and limiting dimensions for transport becomes of prime importance.

As regards first cost, speaking generally, for groups up to 10,000 k.v.a. 50 periods, three single-phase transformers may be more expensive than one three-phase unit, but, when very large outputs are considered, the cost

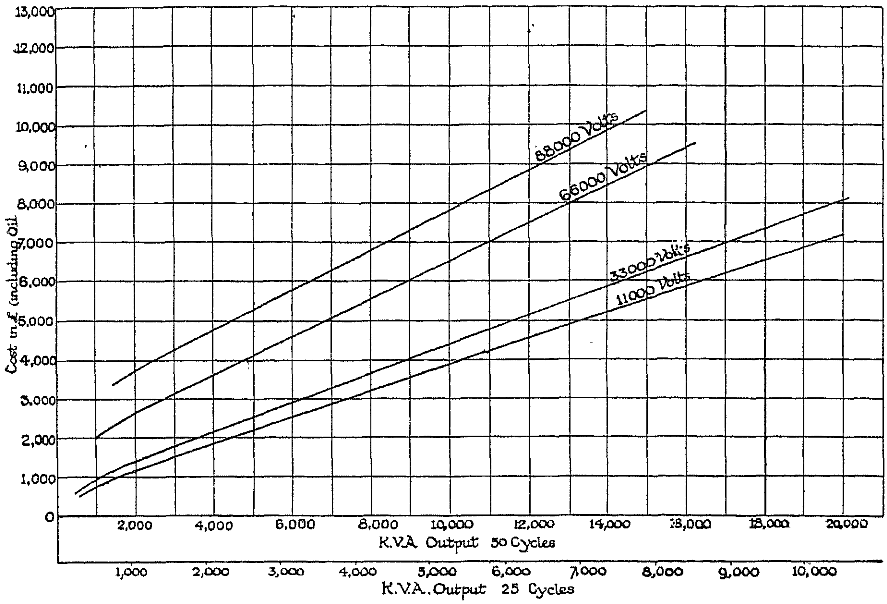


Fig. 19.—Approximate Cost of Three-phase Oil-immersed Water-cooled and Oil-immersed Forced-cooled Transformers

may become approximately equal. This relationship, however, is largely influenced by the type of transformers considered.

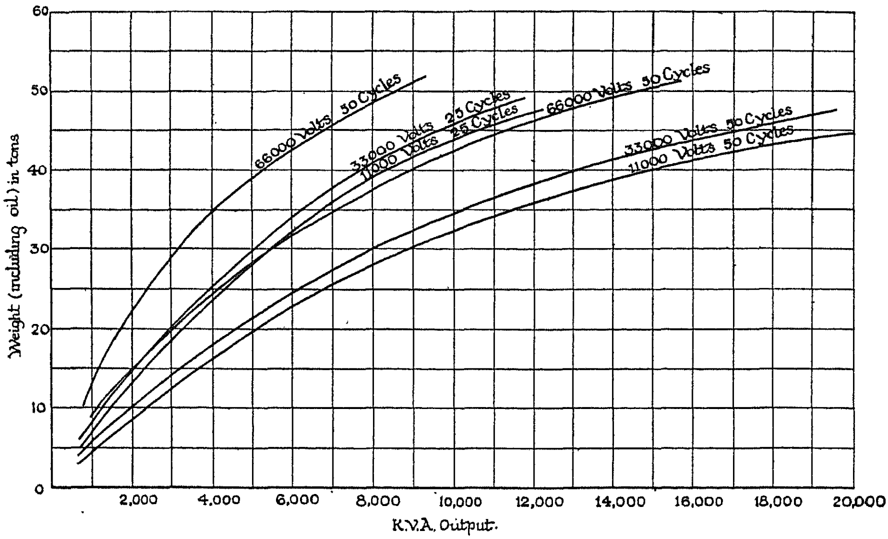


Fig. 20.—Approximate Weights of Three-phase Oil-immersed Water-cooled and Oil-immersed Forced-cooled Transformers

Where a large number of units are to be installed, it will generally be found more convenient to install three-phase units and to have one complete

unit as a spare, but where one bank of transformers only is under consideration, single-phase transformers, with one single-phase unit as spare, have the advantage.

(*c*) *Core Type or Shell Type.*—It is advisable to leave the decision of which type to install to the manufacturer, as, within wide limits, both types are equally satisfactory. It will be found that it is almost universal practice to adopt core type construction for transformers where the current in the high-tension windings is small (approximately below 15 amperes), and that the shell type is generally recognized as more suitable for single-phase transformers of large capacity and low voltage, such as are necessary for electric furnace work. Between these limits, both types are manufactured equally satisfactorily, although each has advantages in several ways.

The chief advantages inherent to shell type construction are:

1. A more robust construction and greater facility for bracing the coils against mechanical damage, which may result from short circuit.
2. There is no tendency towards shrinkage of the insulation between the coils, as the weight of the copper does not bear directly on the insulation.

The chief advantages of core type construction are:—

1. A greater ease of repair in case of breakdown, and,
2. Less voltage between adjacent turns of the windings.

For the purpose of preliminary estimates of the cost of new plant, approximate prices and weights of large three-phase transformers are given in figs. 19 and 20 respectively. The data are based on oil-immersed, water-cooled or oil-immersed, forced-cooled transformers, and in the latter case includes the necessary auxiliaries, such as coolers, pumps, and motors. They are also based on transformers having a temperature rise in the oil of 50° C. above the cooling water. The price curves are based on present-day costs, which are approximately 60 per cent above pre-war costs.

CHAPTER VI

Testing, Erection, and Operation of Transformers

1. Testing.—Before delivery, all transformers are subjected to severe tests to ensure that guarantees of losses and temperature rise are met, and also to ensure that the insulation is satisfactory. The various tests which it is usual to make are as follows:—

Ratio Test.—The ratio of the primary to the secondary voltages is tested in order to ensure that the correct number of turns have been wound in the primary and secondary windings. It is usual to do this by direct voltmeter readings, where the ratio is comparatively small. Where the ratio is high, one method is illustrated in fig. 1. The primary windings of the transformer under test, and of the standard transformer, which has a known number of turns, are connected in parallel, and therefore have the same pressure applied to them. The secondary windings are connected in series in such a way that their voltages are in opposition, and, if equal, no current will flow through the windings. The secondary winding of the standard transformer has tappings brought out from every half turn, and the connection is made to the one which results in no circulating current. The ratio of the transformer under test will then be the same as the known ratio of the standard transformer on the particular tapping employed.

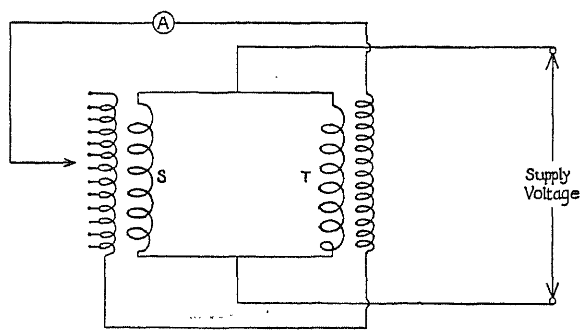


Fig. 1.—Diagram of Connections for Ratio Test

Resistance Measurement.—The resistances of the primary and secondary windings are measured to ensure that the correct section of copper has been used, and also that the copper is of standard quality. When making this test it is advisable to short circuit the winding of which the resistance is not being measured. As the resistance of copper varies at a constant rate with variation of temperature, the rise in temperature of the windings during a load test may be calculated from resistance measurements made

before the commencement of the test, and immediately on its completion, from the following formula:

$$t_r = \frac{(r_2 - r_1)}{r_1}(234 + t),$$

where t_r = rise in temperature (degrees C.),
t = temperature (degrees C.) at which r_1 is measured,
r_1 = resistance at commencement of test,
r_2 = resistance at end of test.

In making the cold measurement sufficient time must be allowed to ensure that the windings are at the same temperature as the surrounding medium.

Iron Loss.—The iron loss is measured by applying normal pressure to either the primary or the secondary winding, and, with the other winding open, measuring the power input. The quantity obtained will be the sum of the iron loss and the I^2R loss of the winding due to the magnetizing current. As this current is small compared to the full-load current, the I^2R loss is usually negligible and may be ignored.

Copper Loss Test.—The measurement of the copper loss is made by circulating full-load current through one of the windings, with the other winding short circuited, when full-load current will flow through the latter, due to the fact that the ampere turns of the primary and secondary windings must balance. The power input measured is the copper loss in the transformer, and the voltage necessary to circulate full-load current is the impedance voltage.

This test also indicates if there is excessive eddy current loss in any of the constructional parts, due to the leakage flux set up by the current circulating through the windings. The copper loss at a particular load is not a constant quantity, but varies with temperature by approximately 0·4 per cent per degree C.

Efficiency.—On account of the difficulties of loading any but the smallest size transformers, the efficiency is usually calculated from the measured iron loss and copper loss by the following formula:—

$$\text{Efficiency percentage at given output} = 100\left(1 - \frac{L}{\text{output} + L}\right),$$

where L = sum of iron loss and copper loss in kilowatts at given output.

In obtaining the iron loss and copper loss at fractional loads from the full load figures, it should be noted that the iron loss is constant, and the copper loss varies as the square of the load. Care should also be taken to see that the copper loss is corrected to the temperature at which the efficiency is required.

Insulation Tests.—The insulation between the primary and secondary windings, and between both windings and the frame, may be tested by

applying twice the normal voltages (with a minimum value of 3000 volts) for a duration of one minute. This is the test specified by the British Engineering Standards Association and is generally adopted. Higher tests or tests for a longer duration are not advisable on account of the danger of straining the insulation.

An alternative method is to apply double normal working pressure across the low-tension winding, which will result in a corresponding over-potential between all adjacent parts of the winding and between the windings and frame.

This test is the only one applicable to transformers specially designed for service where one end of the high-tension winding is to be permanently earthed.

Temperature Tests.—It is not usual or necessary to make a temperature test on all transformers, as with any particular type of tank the manufacturer knows from experience almost exactly what heat it will dissipate with a given temperature rise. Having measured the losses, the temperature rise may be calculated with a sufficient degree of accuracy for normal requirements. On transformers of special design, or when specially required by the customers, temperature tests are made.

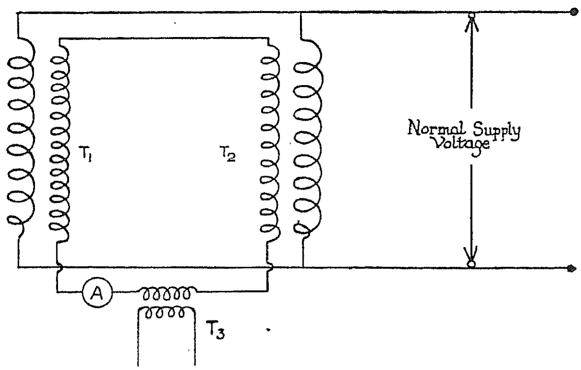


Fig. 2.—Diagram of Connections for Temperature Test (back-to-back method)

T1 and T2, Transformers under test. T3, Auxiliary transformer. A, Ammeter.

On all but the smallest size transformers it is impracticable to load transformers as they are loaded in service, but this difficulty may be overcome in one of several ways. Where two duplicate units are available they may be connected in parallel, and normal voltage applied. The secondary windings are connected in opposition so that no current circulates between the two units. By means of a third transformer, which has its secondary winding in series with the secondary windings of the transformers under test, sufficient voltage is applied to circulate full-load current. The connections for this method are shown in fig. 2.

Where two units which can be loaded in the above manner are not available, the following method may be used. One winding is short circuited, and sufficient pressure applied to the other winding to circulate a current which will give a loss equal to the sum of the normal full load iron and copper losses. This method is not to be recommended, as it necessitates considerable overloading of the transformer windings with a resulting danger of high internal temperatures.

For three-phase transformers the delta-delta method is often the most convenient. The connections are shown in fig. 3. Both windings are connected in delta, and normal voltage supplied to one of them, which gives the normal iron loss. A third transformer is connected in series

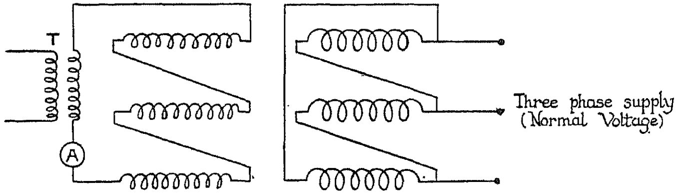


Fig. 3.—Diagram of Connections for Temperature Test, delta-delta method

with the other windings, and sufficient voltage supplied to circulate full-load current.

2. Installation.—In making preparation for the installation of transformers there are a number of points to be kept in mind. The situation

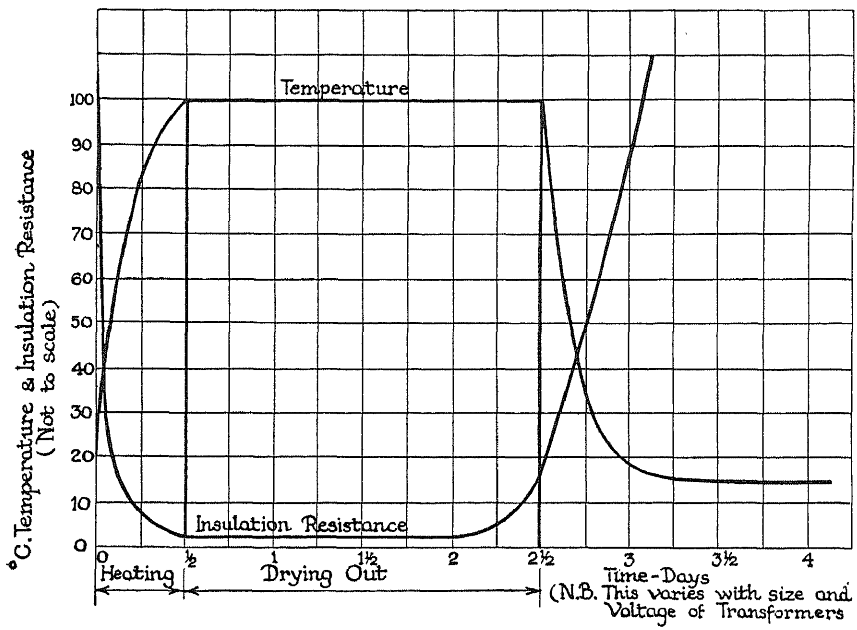


Fig. 4.—Curves showing Variation of Insulation Resistance with Temperature and Time for Oil-immersed Transformers before, during, and after Drying Out. *N.B.*—The actual value of time and insulation resistance are only average representative figures.

should be such that there are facilities for lifting the transformer out of its tank for inspection purposes and in case of breakdown, for in the latter case considerable delay may occur in getting the transformer back into service, if it is not situated where it can be conveniently handled by a crane or pulley block. Where natural-cooled transformers are being installed, it is

extremely important to provide ample space for adequate air circulation; also the transformer chamber itself should be well ventilated. It is advisable to leave a clear space of not less than two feet on all sides of natural-cooled transformers up to 1000 k.v.a. capacity, and three feet for larger size units.

3. Erection.—During the period between delivery and erection, the transformer should be stored in as dry a place as possible, for it is essential that the windings and oil should be thoroughly dried out before the transformer is put into service, and less time will be taken for this process if every precaution is taken to prevent the absorption of moisture during the storage period. The exact procedure in erecting any particular transformer will depend on the method which has been adopted for transportation from the manufacturer's works. Where a transformer is delivered completely dried out and ready for immediate installation, providing there is no delay in putting the unit into service, the drying-out process, which is necessary in all other cases, may be omitted.

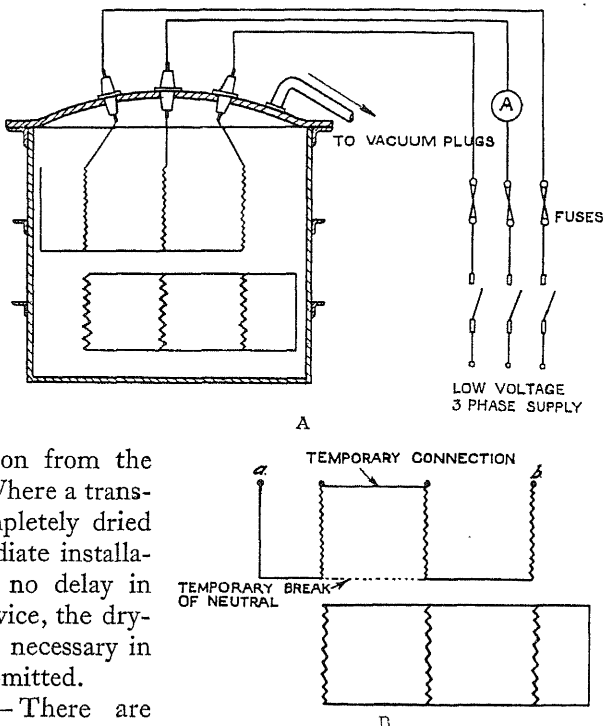


Fig. 5.—Method *a*

A, Three-phase supply. Drying out under vacuum with transformer run on short circuit. Special air-tight cover fitted for drying operation. If only single-phase supply is available connect up as shown in B, the H.T. neutral connection being broken. B, One-phase supply. Supply terminals, *a*, *b*.

4. Drying Out.—There are several methods of removing the moisture from the windings and insulation, and in each case the best indication of the state of the windings is obtained from a series of insulation resistance readings. Fig. 4 shows a typical insulation resistance curve during the drying-out period. At the commencement the insulation resistance may be high, but, if moisture is present, as the windings are heated up it will drop rapidly to a very low value, and will remain constant until such time as the moisture is reduced to a negligible quantity, when there will be a rapid rise. The windings must be maintained at a constant temperature of approximately 100° C. until the rise in the insulation resistance is noted. This may take a period of two or three days, or even considerably longer, according to the state of the windings.

It is equally important that all moisture should be dried out by heating the oil to a constant temperature of approximately 100° C. until samples, taken from time to time, show that the dielectric strength is such that a breakdown will not occur between electrodes separated by a gap of ·15 in., at a lower pressure than 25,000 volts.

A short description follows of four methods of drying out transformer windings. One of these methods will be found suitable for almost any conditions.

(*a*) *Vacuum Process* (fig. 5).—This is only applicable where transformers are supplied having tanks specially designed to withstand a vacuum. As this necessitates a very much stronger tank than is required under normal

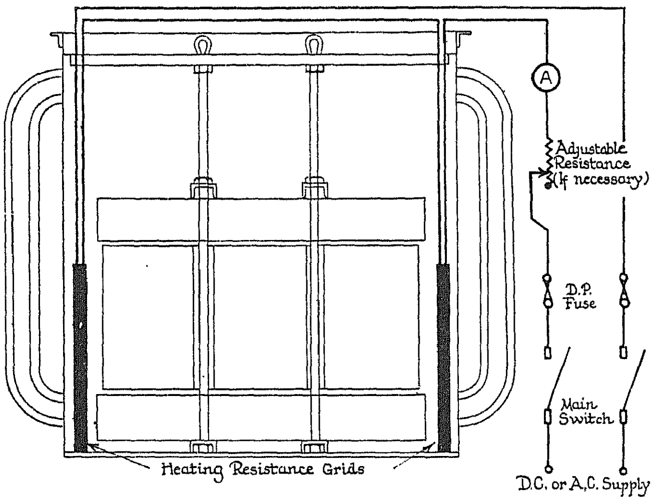


Fig. 6.—Method *b*.—Drying Out in Hot Oil with Heating Resistance Grids

circumstances, such tanks are only supplied for very large transformers. The air is exhausted from the tank until a vacuum of 25 in. of mercury is obtained. The windings are then heated by passing current through them, and the temperature maintained constant at a value of 66° C., which corresponds to the boiling-point of water at this reduced pressure. Insulation resistance readings are then taken, as previously described. This method has the advantage that only a low temperature is necessary, and thus there is little risk of damage to the insulation. When the drying out is complete, the oil may be admitted into the tank under vacuum, thus preventing the formation of air bubbles in the interior parts of the windings.

(*b*) *Drying Out in Hot Oil.*—It is often most convenient to dry out the transformer in hot oil. The oil is heated by resistances suitable for whatever supply of electrical energy is available. The resistances will have to be such that the oil can be maintained at a temperature of approximately 100° C., and, in order to keep them to as small a size as possible, it is advisable to lag the transformer tank with oil sheet or other suitable material, so as to

reduce the heat dissipated from its surface. The method as applied to a three-phase transformer is illustrated in fig. 6.

(*c*) *By Means of Hot Air.*—A further alternative which is particularly applicable to air-blast transformers, but which may be used for other types where it is most convenient, is illustrated in fig. 7. Air at a temperature of approximately 85° C. is blown through the transformer windings. In the case of oil-immersed transformers, the air may pass into the tank through the oil valve, if this is sufficiently large. Suitable baffles are used to ensure that the air is distributed to all parts of the windings. The air should be passed through a drying chamber containing

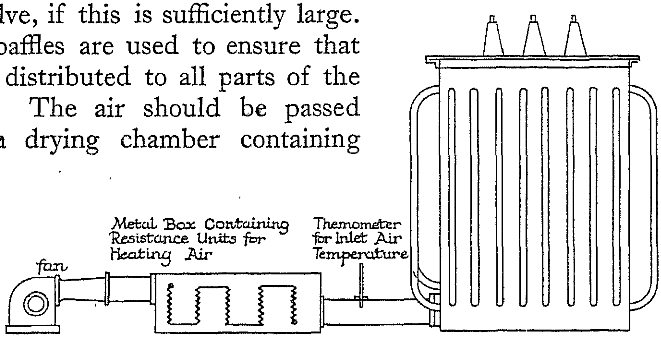


Fig. 7.—Method *c*.—Drying Out by Hot-air Circulation Transformer in Tank. Windings open-circuited. Part of cover removed for air outlet

dry quick lime or calcium chloride, which will absorb any moisture. Approximate figures for the amount of air necessary are as follows:

Transformer Rating.		Quantity of Air per Minute.
500 k.v.a.	....	2000 cubic feet
750 ,,	....	2500 ,,
1000 ,,	....	3000 ,,

(*d*) *Short Circuit Method.*—A further method, which is only recommended where other means cannot be adopted, is to obtain the necessary heat by passing current through the transformer windings. Where possible, this should be done with the transformer removed from the oil, so that as little current as possible is necessary.

The current required will vary according to the size of the unit, and the pressure necessary to produce this current will depend on the impedance of the transformer windings, which is usually stamped on the name-plate. The pressure required in any particular case may be obtained by multiplying the impedance voltage by the appropriate factor given in the second column of the following table:

Transformer Capacity.		Drying Current Required.
Up to 20 k.v.a.	....	1·25 full load current.
20 to 50 ,,	....	1·00 ,,
50 to 200 ,,	....	0·60 ,,
200 to 500 ,,	....	0·40 ,,
500 to 1000 k.v.a.	....	0·20 ,,
1000 k.v.a. upwards	....	0·15 ,,

When a three-phase transformer is being dried out by this method, and a single-phase supply is the only one available, the method of connecting up the windings is illustrated in fig. 5 B.

It will be found that one of the above methods will be applicable for almost any particular case. Whichever method is adopted the utmost care must be taken to avoid excessive temperatures, which would result in damage to the insulation, and also to avoid a possibility of fire, especially in the case of oil-immersed transformers. For this reason the transformer should be under continual observation during the whole of the drying period.

5. Tests on Site.—In addition to the tests which are made at the manufacturer's works it is usual to make certain tests on site before the transformer is put into service.

As already stated the insulation resistance between the windings and the core is measured during the drying-out period to give an indication of the progress being made.

When a transformer has been in store for a considerable period, at the conclusion of drying out, pressure tests, as previously described, may be considered necessary, but in such cases the pressure applied is usually only 75 per cent of the pressure which is applied during the works tests.

When the transformer has been satisfactorily dried and tested, it is ready to be connected up and put into service.

6. Connecting Up.—Where a transformer is being installed which is to run in parallel with an existing unit, care must be taken to ensure that the new unit is connected up in such a manner that the secondary voltages of the two transformers are in phase. Where the supply is single phase there will be little difficulty in obtaining this condition. On three-phase systems, as previously pointed out under the discussion on parallel operation, it is essential that the transformer should have combinations of connections of the primary and secondary windings, which give the same phase displacements between the primary and secondary voltages. Providing the manufacturer has been advised of the necessity of parallel operation on the placing of the order, it should only be necessary to connect the new transformer strictly in line with the diagram of connections supplied with it. If such is not the case, some little difficulty may be experienced in finding the correct terminals on one transformer to join to the respective terminals of the other transformer. The usual method is to connect up the primary windings in parallel and to join together one secondary lead of each of the transformers: by taking readings of voltage across the remaining secondary leads it is usually possible to find the correct method of connecting up.

When this has been accomplished it is advisable to run the transformer with the secondary windings open circuited for a few hours before switching on load, in order to ensure that the windings are in order.

7. Maintenance.—To obtain entirely satisfactory results from any transformer installed, it is necessary that periodical inspection is made of each unit. The length of time which should elapse between such inspec-

tions will depend to a certain extent on the size, voltage, and conditions of service, but in general it should be of the order of twelve months. The transformer should be lifted out of its tank, if oil-immersed, and careful inspection made of all clamping bolts to ensure that they are tight. Where the coil bracing arrangements are such that they may be adjusted to take up any shrinkage that has occurred in the windings, this adjustment should be made. As far as possible the coils and windings must be kept clean, and particular attention paid in tubular tanks to see that there is no obstruction in any of the tubes. With water-cooled transformers it may be found necessary to clean the cooling tube, as there is a possibility of scale being formed, which interferes with the conduction of the heat to the cooling water. In all units which are oil immersed, the state of the oil is of the highest importance, for unless this is in the best possible condition, the life of the transformer may be reduced considerably. A small quantity of the oil should be run off from the base of the transformer and its dielectric strength tested. If this is not satisfactory it will indicate that the oil contains moisture or other impurity.

8. Oil Filtering.—In such cases it is advisable to dry and filter the oil and repeat the test until satisfactory test results are obtained. The most convenient method of doing this is to employ an oil drying and purifying outfit, such as is illustrated in fig. 8 (see Plate facing p. 84). This consists essentially of a motor-driven pump, which circulates the oil through a strainer to remove any solid matter which may be present, and also through a filter and dryer. The filter consists of a number of chambers containing filter paper, through which the oil is forced. Where the oil is not in a bad condition it is often sufficient to pass it once through the outfit, but in some cases the process may have to be repeated several times before the moisture is removed. Wherever possible it is advisable to pump the oil from the transformer tank into some other containing vessel, but, where this is not possible, oil may be drawn from the base of the transformer tank and returned to the top until such time as a sample taken from the bottom proves satisfactory.

9. Oil.—As the majority of transformers are oil immersed, and also as the continued satisfactory service of such transformers is dependent to a large extent on the quality of the oil, it is important that only oil of the highest quality should be used. The chief characteristics of a satisfactory oil are as follows:

(*a*) Good insulator having high dielectric strength.
(*b*) High thermal conductivity.
(*c*) High specific heat.
(*d*) Low viscosity.
(*e*) Capable of standing operating temperature without carbonization or producing sludge.

Of the above characteristics the first and last are the most important. The dielectric strength is an excellent indicator of the state of the oil,

particularly in showing the presence of moisture, as ·01 per cent of moisture will reduce the dielectric strength by 50 per cent. Impurities of any kind have a similar though less marked effect.

The deposition of sludge occurs to some extent with all transformer oils. The deposit appears to be due to the presence of air in contact with the oil, and is accelerated by the presence of metal. Sludge is a bad conductor of heat, and therefore liable to cause high internal temperatures in coils which are covered with it.

A good oil should meet the following requirements:

Flash point—using Pensky Marten apparatus ..	170° C.
Loss by evaporation, 8 hours at 100° C.	3 per cent.
Solidification	−5° C.
Viscosity—using Redwood viscometer, 15° C. ..	500 seconds.
,, —time for outflow of 50 c.c., 50° C. ..	90 ,,
Disruptive strength ($\frac{1}{2}$ in. spheres, ·15 in. apart) ..	22,000 volts.

Sludge characteristic.—After passing a current of air through the oil at 150° C. for 45 hours in the presence of metallic copper, the solid deposit must not exceed 1 per cent.

Oil-testing apparatus is now manufactured in compact form, and such an equipment may be considered an essential accessory to all large transformer installations.

CHAPTER VII

Protection of Electrical Network

Electrical system; protective systems; use of reactances

1. Electrical System.—In the switching equipment it is possible to make very wide variations, and for a given plant the cost of one arrangement may easily be two or three times that of another. Elaboration in switchgear may be justifiable if advantages are obtained in the direction of:

1. Greater freedom from complete shut-down of the system.
2. Limitation of damage due to faults or incorrect operation of plant.
3. Greater flexibility in connection between main units of plant.
4. Increased facility for repairs or cleaning.
5. Safety for operators of plant.
6. Minimized fire risk.

The value to be placed on each of these points will depend largely on the purpose for which power is used and also on the size of the development. For instance, if a small plant be established purely for domestic lighting and power purposes it will be better to take some risks, even of total shut-down, rather than increase capital charges. On the other hand, with a plant serving electric furnaces, or employed on electrolytic work, the consequences of a few minutes interruption of supply may be sufficiently serious to warrant every elaboration.

In a large power plant the increase in cost necessary to obtain added flexibility is relatively unimportant, while the effects of trouble are much more widely felt.

It is not possible to dogmatize in regard to the correct equipment for a given size of plant, on account of the many factors which affect the situation. The underlying principles of the various arrangements are discussed hereafter, and the advantages and disadvantages attending their employment should be considered in every projected development.

The simplest system of connections is that shown in fig. 1. In this case all generators are connected in parallel to a single set of bus-bars, and all feeders taken direct from these bars. Distribution is at generator voltage, so that such an arrangement is naturally limited to plants serving a comparatively small area, with a reasonably well distributed load.

The single bus-bar system is used almost exclusively in direct-current plants, which are not often of large capacity, and in which the voltage is

sufficiently low to make it possible to carry out cleaning operations while the connections are alive. On all alternating-current work it is desirable, and where the pressure exceeds 650 volts it is essential, to install an isolating switch between each circuit-breaker and the bus-bars, so as to make it possible to clean the oil circuit-breaker in safety. The bus-bars with this arrangement can only be cleaned when alive, or when the whole plant is shut down.

With the duplicate bus-bar system shown in fig. 2 greater flexibility is obtained. Each circuit is provided with the usual circuit-breaker and also

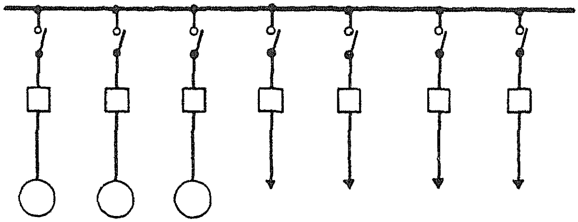


Fig. 1.—Simple Bus-bar System

two isolating switches. By closing appropriate isolating switches, connection can be made to either set of bus-bars. Used in this manner, these isolating switches are more generally termed selector switches, although the only difference is one of function and not of construction.

Normally only one set of bus-bars is in use, giving in effect the connections shown in fig. 1. For cleaning and repair, however, all circuits can be transferred to the auxiliary or "hospital" set of bars, thus leaving the main bars dead and safe to touch. Further, should it be desired to work certain feeders

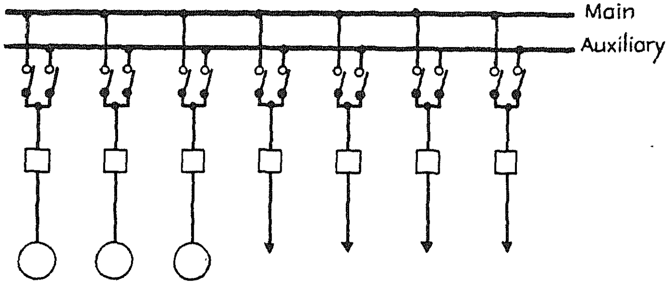


Fig. 2.—Duplicate Bus-bar System

under conditions different from the remainder, this can be accomplished by connecting them, with a sufficient generating plant, to the "hospital" bars.

For example, one feeder may be overloaded temporarily, so that the voltage at the receiving end would be too low, were supply from the generators at normal pressure. By segregating out this feeder with its generating plant, the supply voltage can be boosted up as required, without affecting other parts of the system.

In systems supplying long transmission lines, it is usually desirable to try out separately a line which has been under repair, before paralleling it

with the rest of the system. In this case the duplicate bus enables the operation to be easily performed, by separating out also a single generator of sufficient capacity to supply the full charging current of the line in question.

There is a further use for the duplicate bus-bar, occasionally found on systems transmitting power overhead. Should one wire of a feeder become earthed, it is possible to separate the feeder from the main system and definitely earth that conductor at the power station while the insulators are being replaced. If the neutral point of the A.C. generators is normally earthed, this connection must be removed on the plant serving the feeder under repair. It may be noted that this practice is not free from objection, as, although it enables supply to be maintained instead of shutting down for repair, the unearthed conductors are subject to greater potential stresses than usual.

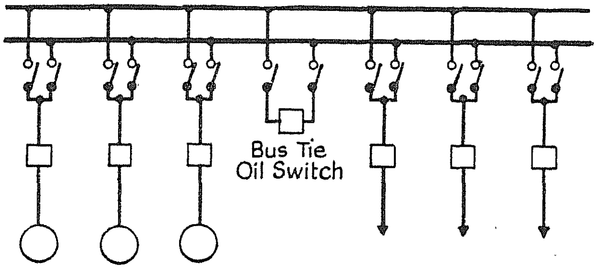


Fig. 3.—Use of Bus-tie Switch with Duplicate Bus-bars

Isolating and selector switches are usually of the air-break type and are not fitted with any quick-acting flicker blade. It is consequently only feasible to make or break with them very small currents. In fact it may be taken as a rule that no current whatever should be broken on single-pole isolating switches. Where all the poles are coupled together, remote mechanically operated isolating switches may be used to break the charging currents of short transmission lines or the magnetizing current of small transformers.

When transferring circuits from one set of bars to the other it is possible to parallel the bus-bars, change over the circuits, and subsequently, after carefully adjusting the loading on generators to correspond with their feeders, to break the bus-bars apart, all on the selector switches. While in many plants this practice is the only alternative to a momentary shut-down for transfer, the operation is greatly facilitated by the use of a bus-coupling oil switch (fig. 3).

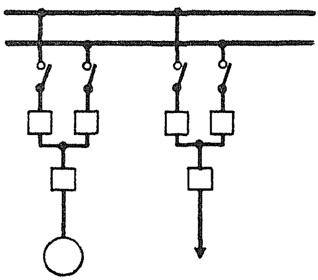


Fig. 4.—Oil-selector Switches

With an oil switch which can be used to break the connection between the two sets of bus-bars, there is no occasion for the same careful adjustment of load distribution between generators, since this switch will not be damaged by an arc. As soon as the bus-coupling oil switch is opened, each group of generators will be independently adjusted to take up the load.

An alternative method of attaining the same facility of operation is to use oil-immersed selector switches, as shown in fig. 4. Using these, a special

bus-coupling oil switch is unnecessary, since any pair of selector switches can be used to connect or disconnect the two systems of bus-bars. Oil selector switches are more quickly operated than the usual air-break type. This advantage is particularly noticeable when selectors and main oil circuit-breakers are operable from the same point. On the other hand, the space occupied and the first cost are largely increased, so that on the whole the oil-immersed bus-bar coupling switch will generally be found preferable.

In all the schemes thus far described, normal operation is to parallel all

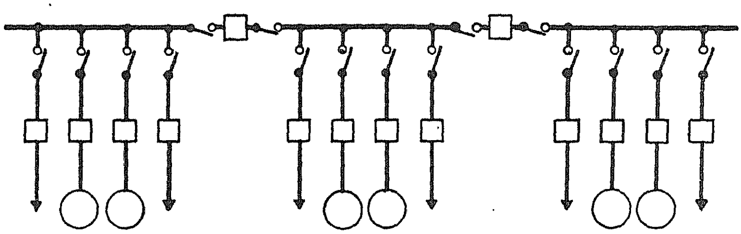


Fig. 5.—Subdivided Simple Bus-bar System

generators through a single set of bus-bars. This is not always desirable, especially with large plants, on account of the very heavy currents which may pass in the event of a fault on the system. Such currents not only necessitate specially stiff bracing of all conductors, but also entail the use of oil circuit-breakers of large rupturing capacity and high cost.

To avoid this difficulty it is sometimes possible to divide the whole system into two or more parts, each having its complement of generators and feeders. The various sections can be tied together by a bus-section oil switch. See

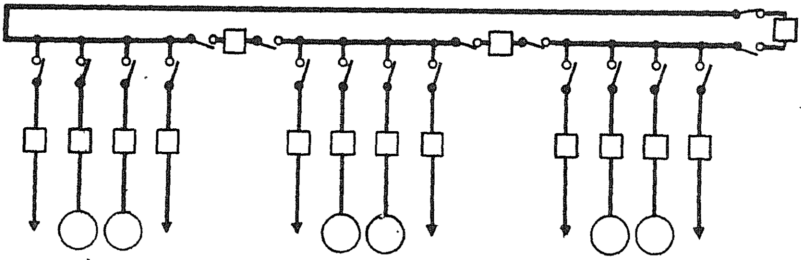


Fig. 6.—Ring Bus-bar System

fig. 5. When the plant is working at or near full load, the section oil switches are opened, giving in effect separate electrical power systems. At times of light load the section switches are closed, and only so many generators run as are needed to supply the whole load. It will be seen that with this method of operation it is impossible for all the generators at once to feed into a fault. The magnitude of the short-circuit current can be limited to any desired extent if the system is capable of sufficient subdivision.

The two ends of a sectionalized bus-bar system may be connected together to form a ring as shown in fig. 6. This possesses the advantage that it is

possible to tie together the outer sections should both be lightly loaded, without interfering with the middle section. As a rule ring bus-bars are operated with all section switches closed, these only being opened when it is desired to segregate a section without affecting the rest of the plant. As closing the bus-section switch will connect adjacent groups of generators, arrangements must be made for proper paralleling.

Maximum flexibility is obtained with a sectionalized duplicate bus-bar system, as shown in fig. 7. In this case the hospital bar can be used if it is desired to parallel any two or more sections, which are not adjacent. If there are more than three sections this cannot be done with a ring bus-bar system. Further, with the arrangement shown any section of bus-bar can be isolated readily for cleaning, whereas with a simple ring system of bus-bars a section of plant must be shut down if work is to be done on the bus-bars.

So far the diagrams shown have been applicable equally to D.C. or A.C. systems, and attention has been confined to those plants in which power is distributed at generating voltage. In the majority of hydro-electric developments this is not possible, owing to the distance between the source of power and point of consumption. It is necessary, therefore, to consider the possible arrangements of connections when transformers are used to step up the voltage for transmission. Only A.C. working will be considered, as being by far the most widely used. The Thury system of high-tension D.C. transmission is briefly dealt with in a later section.

The number of feeders in such cases is usually small, since it does not pay to build a high-tension line to transmit small powers. Moreover, it is frequently possible to preserve a regular proportion between the number and capacity of the generators and of the feeders.

In general the system can be arranged in three ways:

(*a*) With generator and transformer switched as a unit.

(*b*) With all transformers switched independently.

(*c*) With transformer and line switched as a unit.

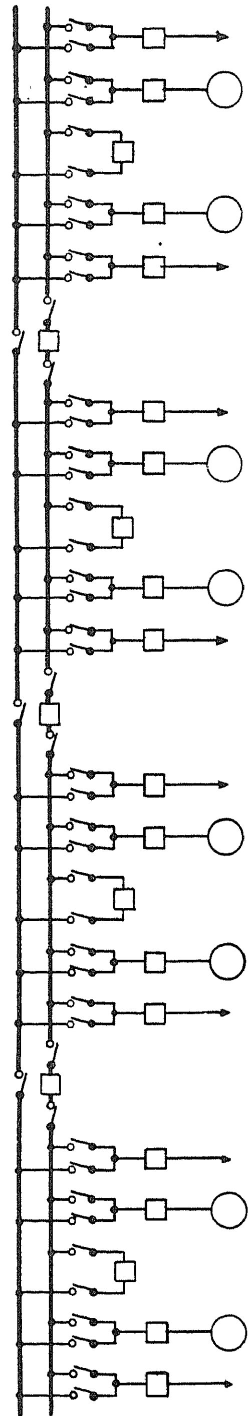


Fig. 7.—Subdivided Duplicate Bus-bar System with Bus-tie Switches

These three methods of connection are shown in figs. 8, 9, and 10 respectively. It will be understood that each of these diagrams is capable of being elaborated with duplicate bus-bars, section switches, &c., after the manner already indicated.

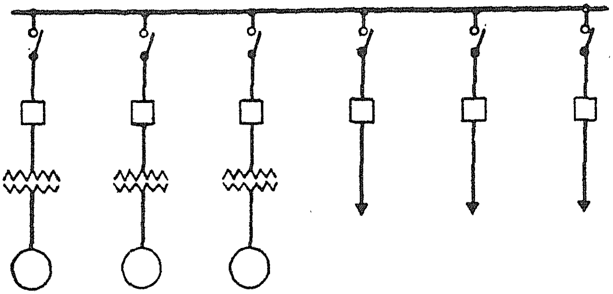


Fig. 8.—Transformer and Generator switched as a Unit

The practice of switching the transformer and line as a unit (fig. 10) was one of the earliest adopted. It presents some disadvantages, in that the transformers may be of varying capacity, corresponding to the requirements of the different feeders, making it difficult to arrange economically for stand-by transformer equipment. Moreover, should a transformer fail, its line is out

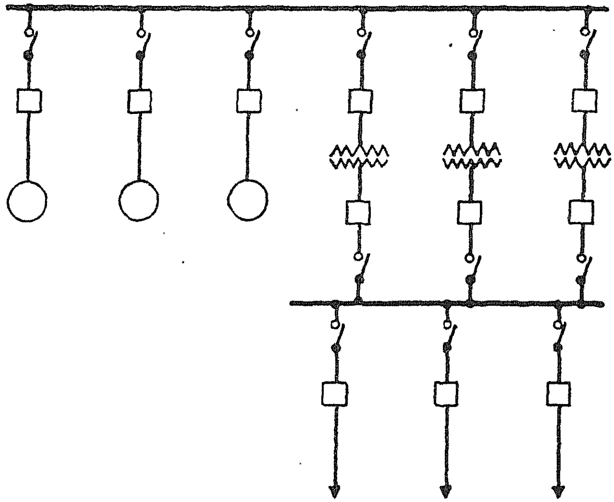


Fig. 9.—Transformers separately switched

of commission until repairs are effected. When switching in an unloaded transformer, considerable surges of magnetizing current may occur, depending on the point in the voltage wave at which connection is established.

If the feeders are in parallel at the receiving end, the effect of opening the switch of one transformer and its line is to give a larger voltage drop on the other feeders than would be the case with other methods of connection when a feeder is disconnected.

The main advantage of this method of connection is that switching surges on the high-tension side are reduced to a minimum. This, however, was of greater importance a few years ago than it is now, as modern transformers, switches, and transmission-line material are sufficiently well insulated to avoid trouble from switching surges.

The first cost of switchgear is also reduced, as all apparatus is insulated for low voltage only. On the whole the disadvantages of this scheme may be said to outweigh the advantages, and it is only rarely adopted to-day.

When the system is arranged so that all transformers are banked together and switched independently, as in fig. 9, it is possible to operate them at maximum efficiency. Breakdown of a transformer does not involve the disuse of a transmission line, and as there are automatic circuit-breakers on both sides of the transformer, finely set protective devices can be employed. There is no difficulty in arranging all transformer units to be of the same size, so that a minimum amount of spare plant is required. The arrangement is more expensive than the other two, and is subject to the rush of magnetizing current when switching on transformers.

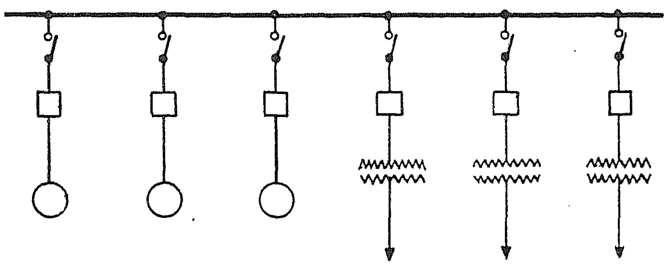


Fig. 10.—Transformer and Line switched as a Unit

Despite these disadvantages the system of connections shown in fig. 9 is probably more widely used than any other. It is particularly suited to cases where transmission is at two or more voltages, as in this case all generators are equally available for supply to any circuit.

When switching transformer units in a system arranged in this manner it is best to close first and open last the oil circuit-breaker on the low-tension side, as by doing this high-tension surges are avoided.

The practice of treating generator and transformer as a unit (fig. 8) is one which has recently been adopted widely. The new super-stations at Dalmarnock, Glasgow Corporation, and at Barton, Manchester Corporation, are cases in point. In plants having large generating units, low-tension switchgear becomes very expensive and bulky, and introduces a certain element of risk, in that a low-tension short-circuit would involve very heavy currents. From this point of view the low-tension gear should be kept as simple as possible.

By running up the generator solidly connected to its transformer, no rush of magnetizing current can possibly occur, this being an advantage gained over both the other schemes discussed.

A further considerable advantage in the schemes shown in figs. 8 and 9 is that separate circuit-breakers are fitted for each feeder. Probably 90 per cent of the service interruptions on systems transmitting power overhead are due to line troubles. With cable systems less than half the troubles are external to the station. So far 30,000 volts is about the highest pressure used on a cable system, so that most hydro-electric plants fall in the first class. British makers are to-day prepared to build cables up to 60,000 volts, but no great practical experience with them is yet available.

Any system of connections which involves tying together two units of plant is of necessity inflexible, since the failure of one unit puts both out of commission. A transfer bus-bar, as shown in fig. 11, may be employed, each generator and transformer (or transmission line) being provided with air-break selector switches as indicated. With this arrangement any one generator may be connected to any other transformer through the transfer bus without interfering with the remaining sets.

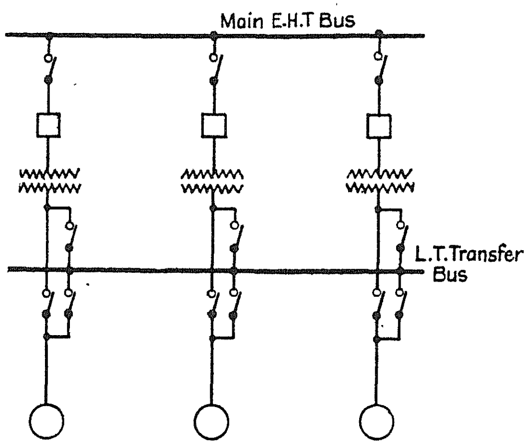


Fig. 11.—Use of Transfer Bus

In a recently built power station in Germany transfer cables have been run between units, each cable terminating in a lug which can quickly be bolted up to the machine or transformer terminals. This scheme is cheap, and probably less liable to break down than a set of transfer bars and selector switches built in the usual way. The work of changing over connections, however, would take considerably longer time than when using proper selector switches.

In all the foregoing diagrams the arrangements are such that should an oil circuit-breaker fail, the plant or feeder which it controls must be out of commission until the breaker is repaired or replaced. A certain amount of stand-by generator and transformer plant is always installed to replace damaged equipment, and in some cases it is arguable that similar provision should be made with the switchgear.

In some European plants a spare oil circuit-breaker of each size is kept ready, and in case of necessity can be connected in place of damaged apparatus. To do this takes up considerably more time than is required to switch in a spare transformer or generator. In other cases a short-circuiting switch is connected across the outer terminals of the usual oil circuit-breaker isolating switches. By closing the short-circuiting switch and opening the other two, repairs can be carried out on the oil circuit-breaker. For the

time being the particular circuit affected is deprived of automatic protection, so that the arrangement involves a certain element of risk.

In certain large American plants using a duplicate bus-bar system such as is shown in fig. 4, each of the selector switches is in fact an oil circuit-breaker, the main circuit-breaker being omitted, giving the connections in fig. 12. Automatic relays are arranged to trip both circuit-breakers at the same time.

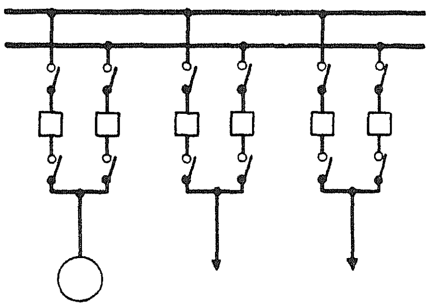


Fig. 12.—Oil Circuit-breakers used for Selection

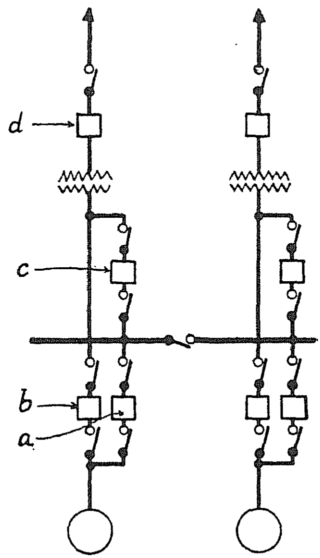


Fig. 13.—Oil Circuit-breakers on Transfer Bus

This arrangement has much to recommend it. If the oil selector switches in fig. 4 are made only of sufficient normal current-carrying capacity, but of small rupturing capacity, interlocks must be provided to ensure that both selectors cannot be opened unless the main oil circuit-breaker is opened first. Otherwise a selector switch might be called upon to open on too great a load and be damaged thereby. Using the arrangement shown in fig. 4, it is a very general practice to use as selector switches, non-automatic devices which are otherwise duplicates of the main circuit-breaker. In such a case the scheme of fig. 12 would actually come out cheaper.

The transfer bus system of fig. 11 is similarly subject to modification, using automatic circuit-breakers, the two possible arrangements being as shown in figs. 13 and 14, the former being the more usual.

Using the scheme shown in fig. 13, by closing circuit-breaker *b* the generator is tied direct to its corresponding transformer. If this circuit-breaker be out of order, the same

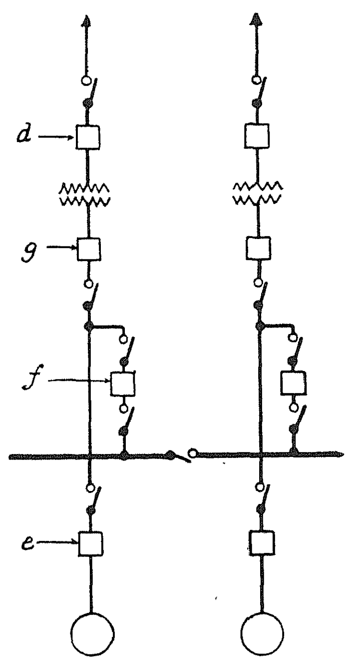


Fig. 14.—Oil Circuit-breaker on Transfer Bus

connection can be established by opening the bus-section isolating switches and closing circuit-breakers *a* and *c*, while these same circuit-breakers can be used in conjunction with the transfer bus to tie together any generator and transformer which do not normally correspond. It will be noted that with this switching system the generator protective device must be arranged to trip out both *a* and *b*, while the transformer relays must trip *b*, *c*, and *d*. This involves the use of a relay wiring transfer switch whenever the transfer bus is in use.

The advantage claimed for the system in fig. 14 is that circuit-breakers *e* and *g* are normally in series, and it is thus possible to get a "second line of defence" if overload relays are used in addition to any other forms of protection. For instance, should the circuit-breaker *g* fail to open in the event of trouble in the transformer, the overload trip should cause *e* to operate. No relay transfer switch is needed in this case, as *e* always is connected to the same generator and *g* and *d* to the same transformer, whether the transfer bus is in use or not.

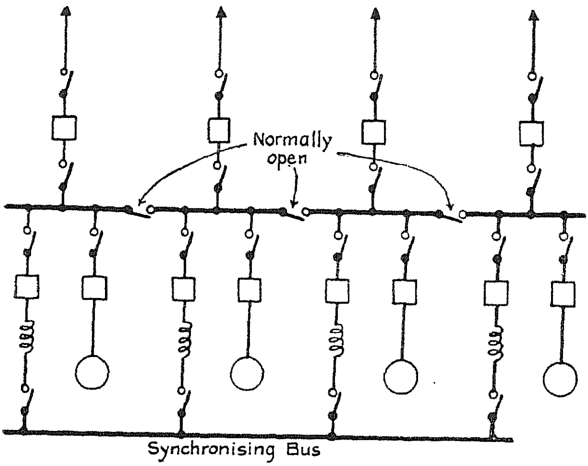


Fig. 15.—Synchronizing Bus-bar Arrangement

An ingenious arrangement has been suggested* to avoid complete reliance on a single circuit-breaker in the case of a system employing a synchronizing bus-bar (see p. 145), without incurring the expense of duplicate circuit-breakers. The normal arrangement of connections to the synchronizing bus is shown in fig. 15. If any one oil circuit-breaker fails it will put out of operation the generator, reactance, or feeder to which it is connected.

In fig. 16 is shown the modified scheme proposed by Mr. Treat. The oil circuit-breakers are arranged in a triangle, so that any one of the three can be cut out of service without preventing normal operation being maintained. The number of oil circuit-breakers is the same in the two schemes. The triangular arrangement requires almost double the number of isolating switches, and would be difficult to work into a neat cubicle arrangement. The final cost would certainly be less than if all circuit-breakers were duplicated.

Numerous special arrangements of switchgear have been employed from time to time, to secure some particular feature of operation. In all cases, however, these schemes are adaptations of the elementary arrangements

General Electric Review, Vol. XXII, p. 922, "The Electrical Lay-out of Large Power Systems", Robert Treat.

described herein, and no attempt will be made to consider them in detail.

2. Protective Systems.—Considerable variations exist in the means adopted to secure automatic operation of circuit-breakers. The earliest forms of relay were so unreliable that, after a few years of unfortunate experience, many engineers decided that a known absence of protection was better than a relay system which failed at the critical moment. This was the case particularly in America, and until quite recently many large plants were built without any automatic switches. This practice has proved expensive, although many non-automatic installations still exist; and as entirely reliable relays have been obtainable for some years, complete automatic protection should now always be installed.

It will be desirable to consider separately the protection of generators, transformers, and feeders.

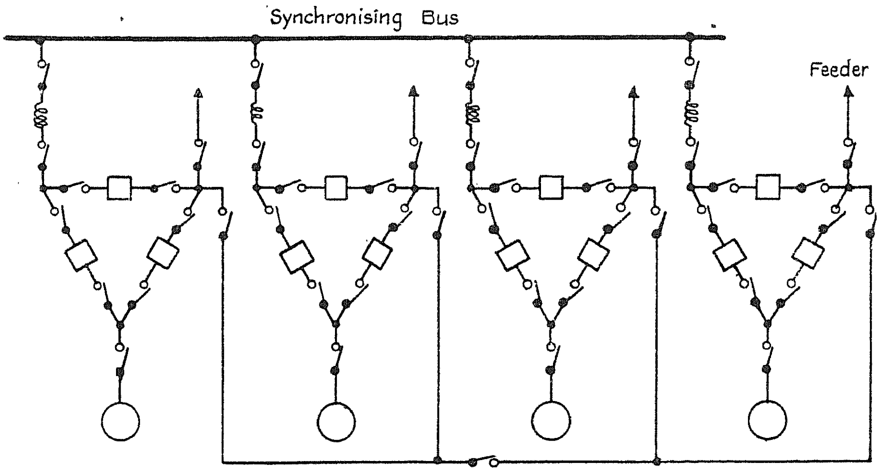


Fig. 16.—Triangular Connection of Circuit-breakers

In any system the object to be aimed at is to open that automatic device nearest to the point at which trouble occurs. Thus in the case of a main feeder short-circuit, the generator circuit-breakers should not open, even though every generator may be overloaded, but the feeder circuit-breaker should operate, and thus avoid interrupting service to healthy feeders. Similarly, if the short-circuit be on a branch feeder, the main station feeder breaker should stay in, and only the sub-station feeder circuit-breaker open automatically.

It follows that the generator oil circuit-breaker must be arranged so as to open only when trouble has developed in the winding of the machine itself or in its prime mover, or when, due to the possible failure of other circuit-breakers, overload conditions have prevailed so long as to threaten to burn out the generator winding. In some instances the generator circuit-breakers are so arranged as to disconnect the set from the bus-bars should anything go wrong with the auxiliaries of the prime mover. Such elaborations are only applied in the case of very large units.

The simplest arrangement for generator protection is to use a reverse power relay only. Should the windings of a generator become short-circuited, all other machines with which it is operating in parallel will supply current into the fault, thus reversing the direction of energy flow in the leads between the faulty machine and the bus-bars. Similarly, should the prime mover of any generator fail, this set will be "motored" by the healthy machines, again resulting in a reversal of power in the circuit between bus-bars and the defective generating unit. In most cases, if a mechanical defect, and not mere failure of steam or water, has caused this motoring, the reverse power will suffice to work a relay.

The movement of a reverse power relay is essentially that of a wattmeter, a contact-making device being carried on the moving element. At least 10 per cent of normal full-load power is necessary to give sufficiently firm contact to pass the current for the circuit-breaker trip coil. This figure of 10 per cent power is usually correct down to about 10 per cent normal voltage. With voltage decreased below 10 per cent, the current necessary may increase in more than direct proportion, and this is frequently the condition when a short-circuit occurs close up to the bus-bars. It consequently often happens that the reverse power relay fails to trip the circuit-breaker at the instant it is most urgently required.

Because the reverse power relay is a simple piece of apparatus, and moreover can be used on any system, whether the neutral point is earthed or not, it is often installed on small plants, despite the element of unreliability. On systems with an earthed neutral, three single-phase relays should be used and not a polyphase relay. The latter is a two-element device, and a single-phase reversal of power might fail to operate such a relay.

Many efforts have been made to produce a true reverse *current* A.C. relay, but without entire success. The best of these instruments is one in which a very fine directional element is used in conjunction with a relay of the overload type, the contacts of the two being in series to close the trip coil circuit. Such an instrument will operate with 2 per cent voltage with current about normal full load, the operating current being about 5 per cent normal full load, with full bus-bar voltage.

Much more reliable operation is secured with differential methods of protection. These are generally only applied to systems in which the neutral is earthed, either solidly or through a resistance. When used on a fully insulated system, they are inoperative when only one phase develops a fault to earth. If a fault subsequently develops on a second phase, leakage current can pass from one fault to the other, and will thus enable the relay to trip. They are based on the fact that the currents at the two ends of a healthy conductor are the same. If the insulation be defective, so that a leakage current can circulate back to the neutral point, a difference will then exist between the incoming and the outgoing currents.

The circulating current system of generator protection (commonly known as the Merz-Price system) is shown in fig. 17. A series transformer is connected in each lead from the generator, and a similar transformer is placed

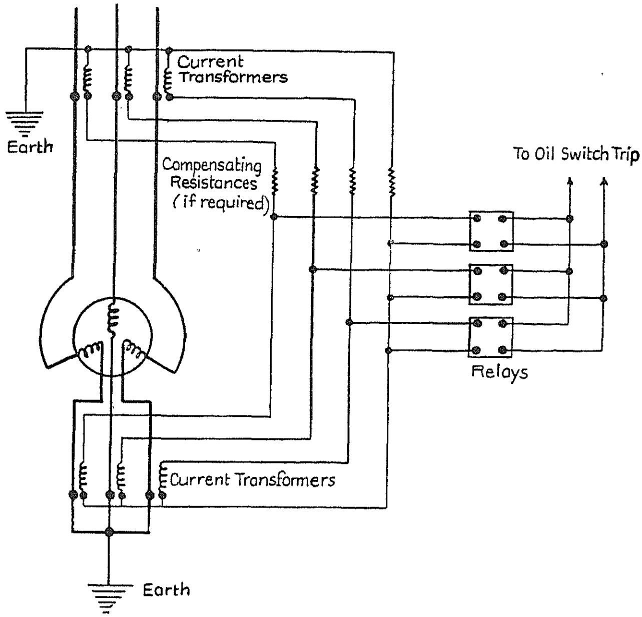


Fig. 17.—Circulating Current Generator Protection

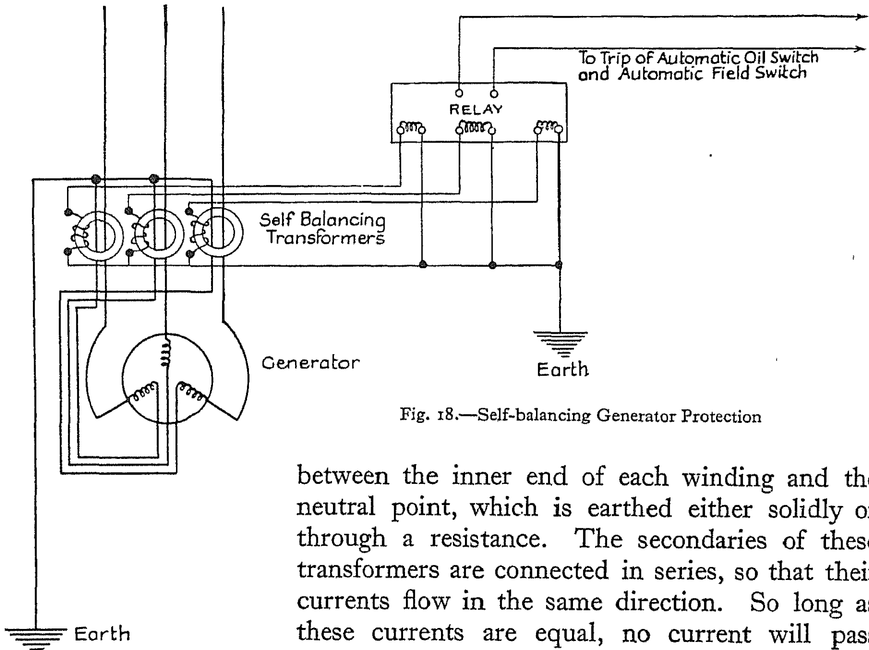


Fig. 18.—Self-balancing Generator Protection

between the inner end of each winding and the neutral point, which is earthed either solidly or through a resistance. The secondaries of these transformers are connected in series, so that their currents flow in the same direction. So long as these currents are equal, no current will pass through the relay, but should any difference exist between them, that difference will pass through the relay coil, and cause it to trip the circuit-breaker.

This method was first developed in England, and has been in use for

several years. Recently it has been taken up in America also, and is now employed on the majority of large plants newly installed.

By placing the outer transformers in the switch cell, protection is secured not only for the generator windings, but also for the cables connecting to the switchgear. If the relays cannot be connected to the point midway between the protective transformers, a compensating resistance is usually inserted in the shorter leads, so as to equalize the loading on the transformers. The ratio of the protective transformers must be exactly the same at all loads,

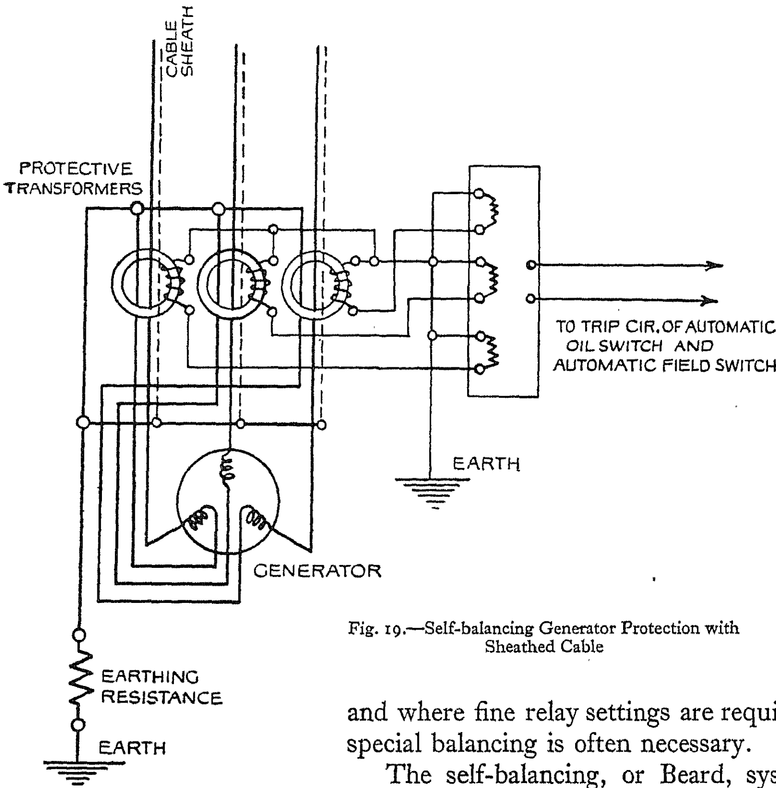


Fig. 19.—Self-balancing Generator Protection with Sheathed Cable

and where fine relay settings are required, special balancing is often necessary.

The self-balancing, or Beard, system is based on a similar principle. See fig. 18. In this case, however, the two ends of each phase winding are brought out and passed through a common iron circuit, on which is wound a secondary, connected to the relay. A magnetic balance is thus obtained instead of a current balance. This system is not only cheaper, but is capable of operating with smaller leakage currents than can the Merz-Price system.

The recent application of the sheathed cable to the self-balancing scheme makes it possible to locate the protective transformers in the pit beneath the generator, and still to protect the cables running up to the switchgear. The arrangement is shown in fig. 19. The cable connecting from the generator to the switch cubicle is provided with a metallic sheath, which is insulated alike from the conductor proper and from the usual lead covering. This

sheath is connected to earth at one point between the generator and the protective transformer. If now a fault occurs between the generator and the switch, the leakage current will traverse the sheath to the point at which it is earthed, and thence through the earthing resistance to the machine neutral. As the currents in the phase conductor and the sheath neutralize each other, the leakage current returning through the neutral conductor excites the protective transformer and operates the relay.

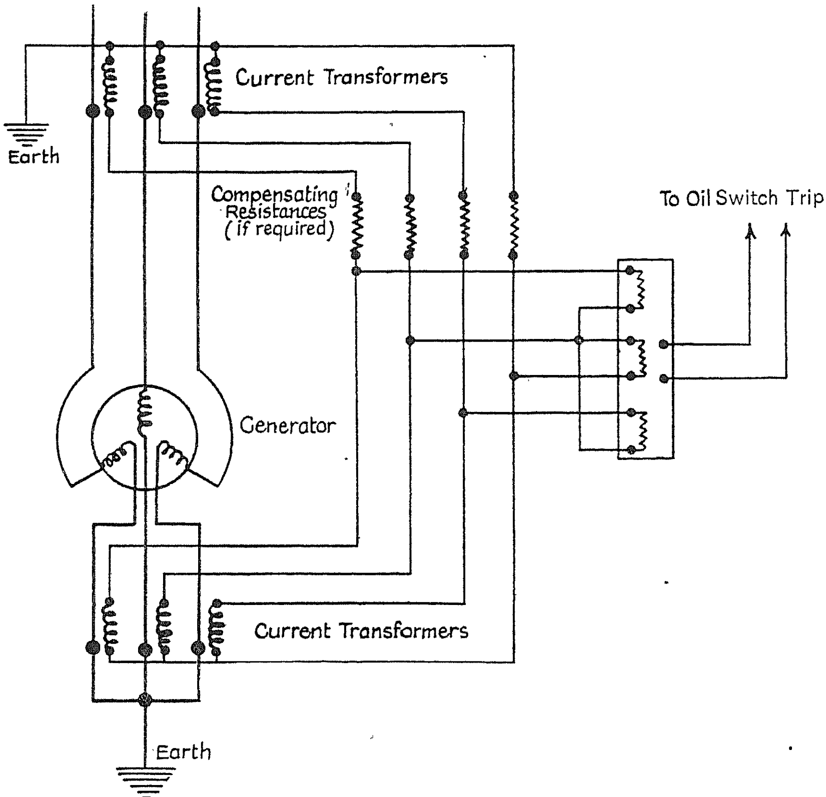


Fig. 20.—Circulating Current and Core Balance Generator Protection

The Metropolitan-Vickers patent scheme, known as the circulating current and core balance system of protection, differs from the Merz-Price circulating current method only in the arrangement of the relays. It is shown in fig. 20. It will be seen that two of the relay elements are connected at one end each to one phase pilot wire, the other ends being commonly connected to the third phase pilot wire. Between this common point and the common return pilot wire is connected a third relay element. A fault to earth results in current passing through the last relay. A fault between phases leaves it unaffected, however, but does operate one of the other two relay elements. With this scheme a very fine leakage setting can be obtained.

In conjunction with any of these forms of generator protection, it is

necessary to install an automatic field switch, commonly termed a "field killing" device. This consists of an electrically operated switch in the generator field circuit, which is actuated by the balanced protection relay. At the same instant as the generator oil circuit-breaker is tripped, this field switch disconnects the exciter, and preferably open-circuits the main field winding or closes it through a discharge resistance. In this way a fault is prevented from burning itself out after the oil circuit-breaker has been opened. In practice this form of protection operates so quickly that it is frequently difficult to see the point of insulation breakdown, when the defective winding has been withdrawn from the generator.

A somewhat similar arrangement is sometimes used, in which the exciter field is short-circuited, but this is not so quick in operation, and is only applicable to cases where each generator has its own exciter.

The field circuit-breaker is only actuated when the protective relay operates, and it does not open when the oil circuit-breaker is opened in the normal course of station operation.

In addition to these electrical automatic devices, water-wheel generators may also be fitted with an overspeed trip, actuated by the governor, so that when the prime mover exceeds a limited percentage above normal speed, the generator is either disconnected from the bus-bars, or a resistance is inserted in the field circuit.

Another device sometimes installed is an over-voltage relay. If the generators in a station suddenly lose a large proportion of their load, due to the opening of a feeder circuit-breaker, the voltage may be forced far above normal. This is on account of the fact that the excitation will be that corresponding to the heavy load, and, further, the speed of the water-wheel may momentarily increase, and raise the excitation voltage if direct-driven exciters are used. Voltage regulators, if installed, should take care of this, but some types are too sluggish, and thus necessitate the additional protection. This over-voltage relay is employed to act in the same manner as the over-speed contacts referred to in the previous paragraph.

It should be noted that in a low-head plant, the governor can usually safely be set so sensitively as to check any serious speed increase, even when full load is thrown off. On a high-head plant, it may be necessary for the governor to take three or four seconds to check the speed in these conditions, and the automatic device becomes necessary.

Continental practice in the matter of generator protection has hardly advanced beyond the reverse power relay stage, these relays frequently being fitted with time-limit devices. By this means the oil circuit-breakers are protected from the most severe duty, but serious risks are run of burning out the complete generator in the event of insulation failure.

There is no doubt that the correct practice at the present stage of relay development is to install self-balancing relays with automatic field switch, if the machines are of any size or importance in the power-supply system as a whole, and in addition reverse power relays to take care of prime mover

failures. For small, unimportant machines, instantaneous reverse power relays only may be employed.

For transformers, also, the circulating current is the most satisfactory system of protection available. The principle is the same as in the case of generator protection, save that the high- and low-tension series transformer ratios are such that normally their secondary currents balance. Operation of the relay trips the oil circuit-breakers on both high- and low-tension sides. See fig. 21.

Transformer protection by this method calls for some special features. The magnetizing current will form a permanent out-of-balance between primary and secondary, and it is necessary to set the relay to such a value as will prevent it operating on magnetizing current alone.

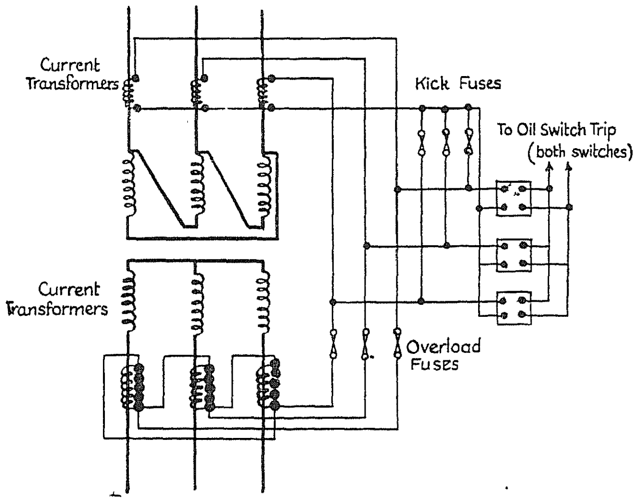


Fig. 21.—Circulating Current Transformer Protection

The current rush at the instant of switching in a transformer may exceed for a few cycles even the normal full load, and small fuses are therefore connected across the relay coils. These fuses are very light, so that an out-of-balance current, sustained, quickly melts them and actuates the relay.

For balancing to be obtained it is essential that the secondary currents from the protective transformers be in the same phase relation. This is accomplished by varying the connections between secondaries on each side.

Overload relays, either time-limit or instantaneous, are frequently employed for transformer protection, although clearly inferior to the balanced current system, which can be made to trip on an unloaded transformer with a leakage current much below normal full load. Under like conditions, using overload relays, the fault would have to develop until a current considerably in excess of normal was passed.

Where transformers are banked in parallel, and always pass power in one direction, they may be protected with overload relays at the generator side, and with reverse power relays at the out-going side, just as is hereafter de-

scribed under the protection of feeders in parallel. This arrangement is no more sensitive than the plain overload relay on each side, but it discriminates between sound and defective transformers in a way that the latter would not do.

Generalizing, it may be concluded that the correct manner in which to protect transformers is to employ current balancing, with small "kick" fuses across the relay coils.

Much ingenuity has been devoted to the development of systems of feeder protection, and it is proposed to discuss only those arrangements which are of wide general application.

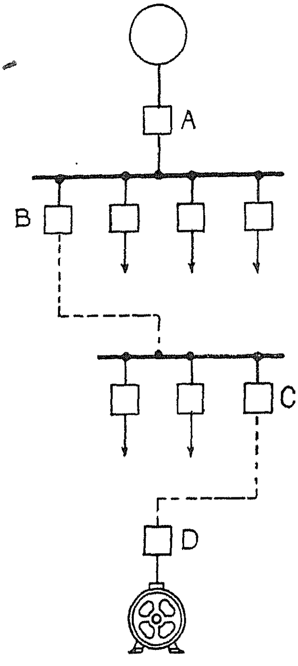


Fig. 22

In any system there will be several circuit-breakers in series, such as the generator breaker A, the main feeder breaker B, the sub-station feeder breaker C, and the consumer's circuit-breaker D (fig. 22). If all of these circuit-breakers have instantaneous overload release, it is in every way possible that a heavy short-circuit on the consumer's premises may open the whole series, right up to and including the generator circuit-breaker. This is even possible, though not quite so probable, if the relays are of the inverse time-limit type, since the curves of these all approach the zero time line at high current values.

The first reliable method of ensuring the correct sequence of operation was to set each relay to trip in a definite time, irrespective of the magnitude of the overload. Thus D would be instantaneous, C would trip after one second, B after two seconds, and A after three seconds. On a large system, with many circuit-breakers in series, the time delays close in to the power station may become dangerously long, as a severe short-circuit, sustained for a few seconds, can do much damage.

The inverse-adjustable, or compensated overload relay was developed to meet this difficulty, and it now enjoys a wide application, especially in America. The relay is of the induction type, but is supplied from a small transformer or torque compensator, which becomes saturated on heavy currents, and thus limits the disc speed to a predetermined maximum. By varying the tappings on the torque compensator, the maximum disc speed (and thus the minimum operating time) can be altered, and by simultaneously changing the current settings, the relay will give a series of curves of characteristic inverse shape at moderate overloads, but with definite time differences at heavy overloads. See fig. 23.

With such instruments it is easily possible to secure proper selection on

three or four circuit-breakers in series with a maximum time delay of one second.

Where two or more feeders are worked in parallel, as in fig. 24, and normally pass power in one direction only, the circuit-breakers at the generating station end may be fitted with overload time-limit relays, while breakers C and D at the sub-station end are operated by reverse power

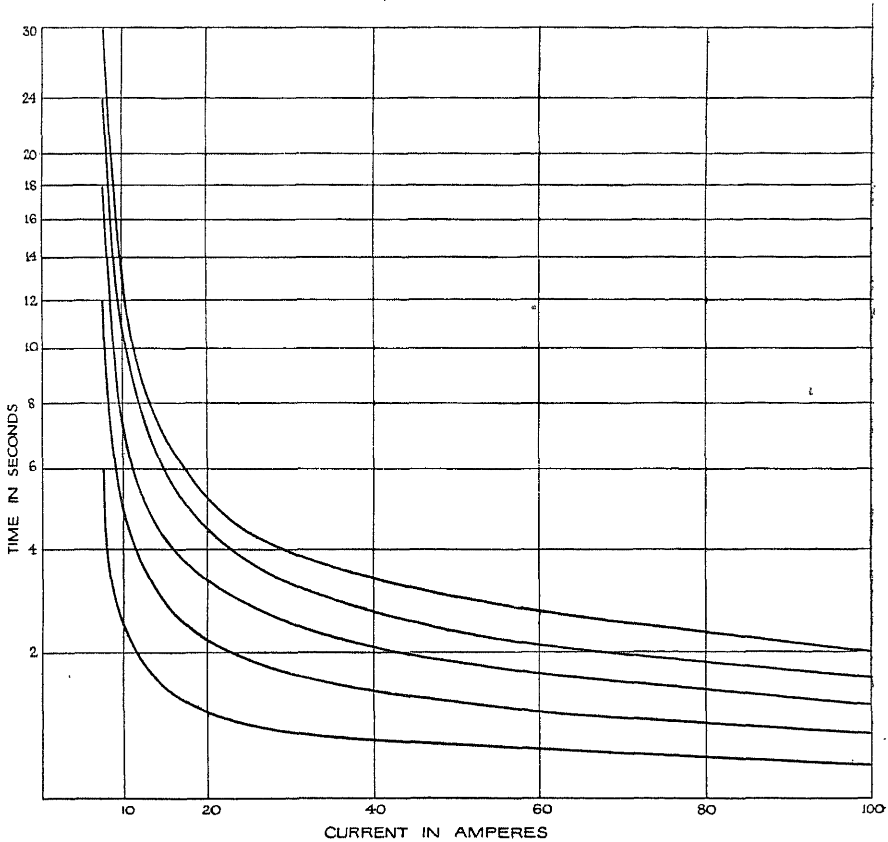


Fig. 23.—Typical Curves of Compensated Overload Time Limit Relay

relays. If now a fault occurs on one feeder at the point X, current will flow into it both through circuit-breaker B, and also through A, C, and D. If the leakage is in excess of the load, the direction of flow will be reversed through the relay on circuit-breaker D, which will open, leaving B to come out on overload.

It would not be correct to use overload relays at both ends of paralleled feeders, since, under fault conditions, at times of no load or light load the currents in A, B, C, and D might be so nearly the same as to cause all relays to operate simultaneously. Where parallel feeders are used to tie between two generating stations, and may consequently be carrying power in either

direction, overload relays at both ends are sometimes used on account of the low cost of such an arrangement, and despite the possibility of non-discriminating action.

A ring system having only one point of supply can be protected by means of overload time-limit relays at the power station, and reverse power time-limit relays at the sub-stations. All these relays may be either of the definite time

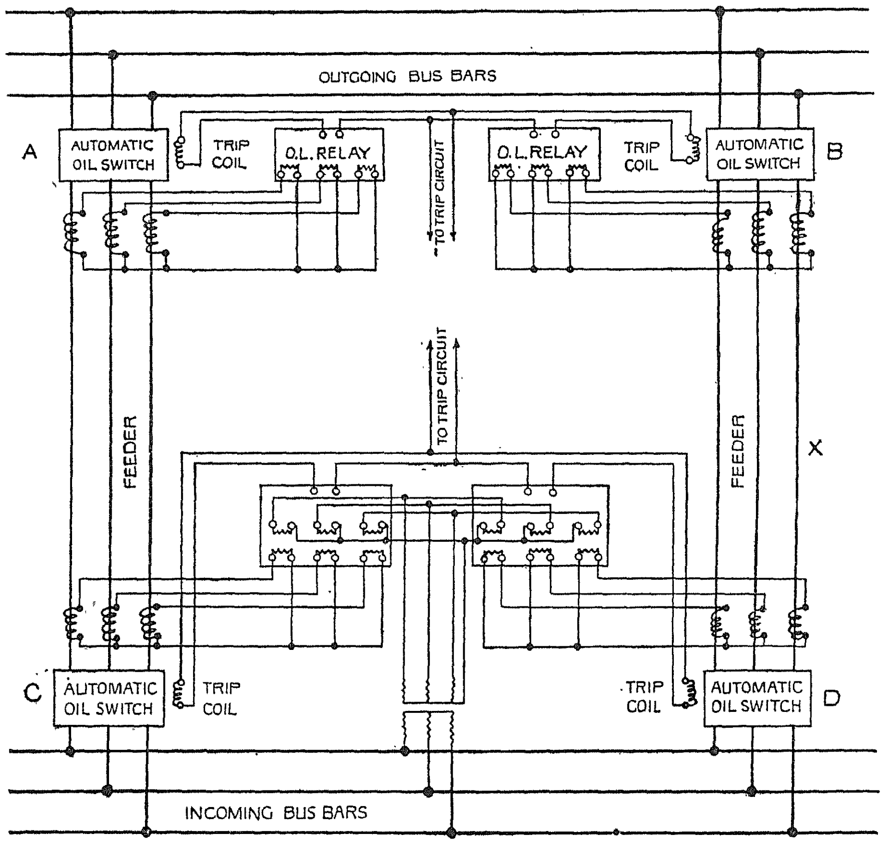


Fig. 24.—Protection of Paralleled Feeders with Overload and Reverse Relays

type, or of the compensated type, having adjustable minimum time delay. Reference to fig. 25 will make it clear that a short-circuit occurring at any point on the ring feeder system will cause to operate only the two circuit-breakers immediately adjacent.

If there be more than one source of power in the ring feeder system, this method of protection becomes very difficult, since the time settings must be arranged in sequence from the point of power-supply, which point would be a shifting one, depending on the load conditions on the system as a whole.

In certain instances where the load variation follows very clearly defined changes through the day, the relay settings are changed to suit altered operating

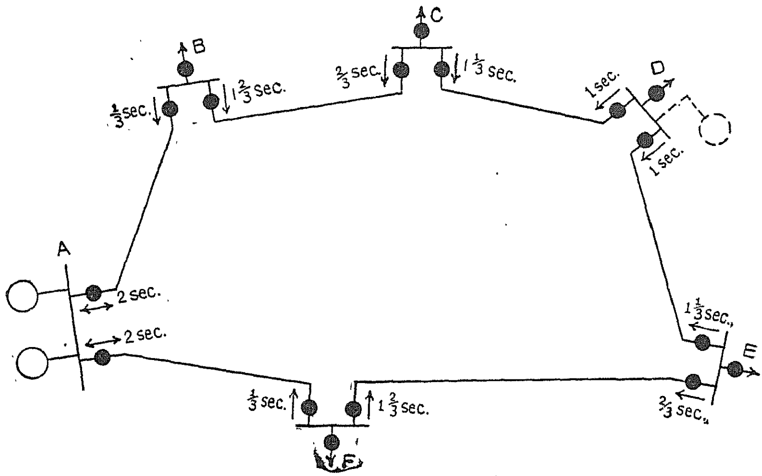


Fig. 25.—Ring System with Definite Time Relays

conditions, instructions for such changes being issued by the load dispatcher for the system. In general, however, such an arrangement would be impracticable.

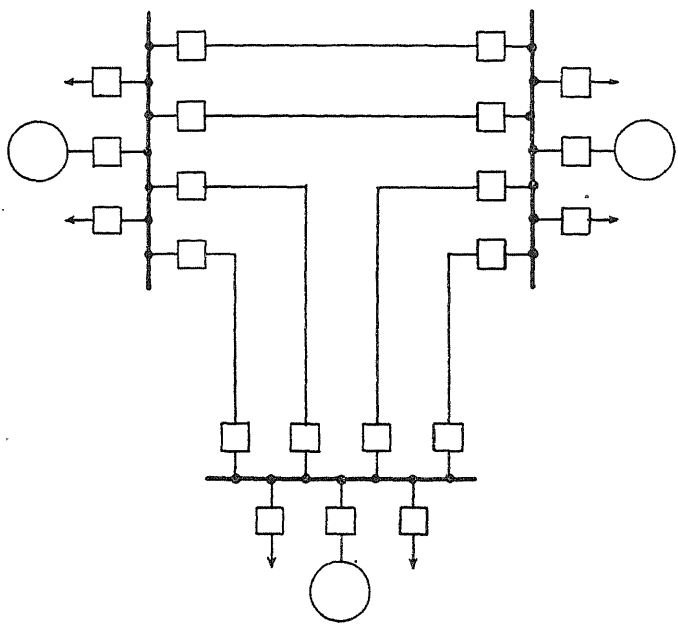


Fig. 26

On systems having long transmission lines and several generating stations, this form of ring system is never used, as although methods of protection described hereafter would be workable, the capital outlay involved by their use would be too great. The most satisfactory practice is to run duplicate

tie lines between generating stations, and serve all power-supply feeders normally from one point. Alternative routes to any supply point may be provided, for use in case of need. Similarly all the generating stations may be so grouped that their duplicate tie lines form in effect a double ring system (fig. 26).

The balanced power method of protecting duplicate feeders is one which has been introduced in America comparatively recently, and which has been found extremely satisfactory in giving discriminating operation on duplicate feeders which may normally supply power in either direction. The scheme is in fact applicable to any number of cables in parallel.

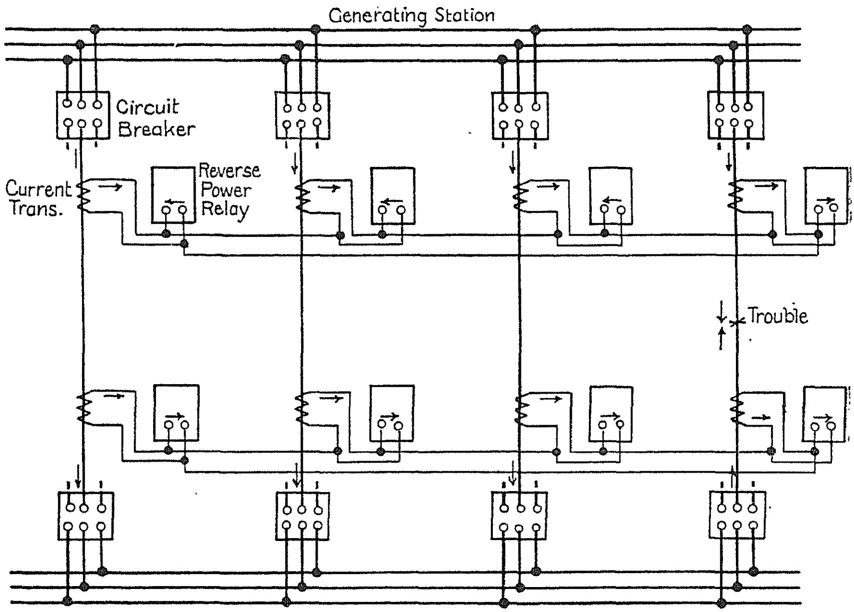


Fig. 27.—Balanced Power Protection for Paralleled Feeders

Referring to the diagram (fig. 27), it will be seen that at each end of each feeder is connected a reverse power relay, the arrangement being such that this relay tends to close its contacts when power is flowing away from the adjacent bus-bars. The secondaries of all current transformers are in series, and so long as the currents in these are the same they will merely circulate, and will not tend to traverse the higher impedance path through the relay coils.

If the balance of the currents be disturbed, the difference will pass through the relays, but as shown in the diagram it will only be in the direction to close the contacts on those relays connected in the circuit of the defective cable.

When the oil circuit-breaker opens it also works a small auxiliary switch which short-circuits the series transformer in that circuit, and thus leaves the remaining transformers balanced against each other.

As stated above, this scheme has for outstanding advantage the fact that it can be applied to tie lines which may pass current in either direction.

It does not protect against straight overloads, which similarly affect all the paralleled feeders. Also the circuit-breakers of the last feeder left in circuit are rendered non-automatic, since there is nothing against which to balance.

The most serious objection, however, is that if a new feeder is to be paralleled with others already on load, it will trip out if the sub-station switch is closed first, or if the switch at the supply end is first closed, then all the feeders on load will come out. The electrical solution so far offered is to set the relays for so high a current that they will not trip under these conditions, but this is to lose all the advantages of low operating current (less than normal full load) possible when once the lines are at work. The best thing to do is to hold the relays inoperative during the moment the new feeder is being cut in. As soon as it can carry its share of the load, equilibrium will be established.

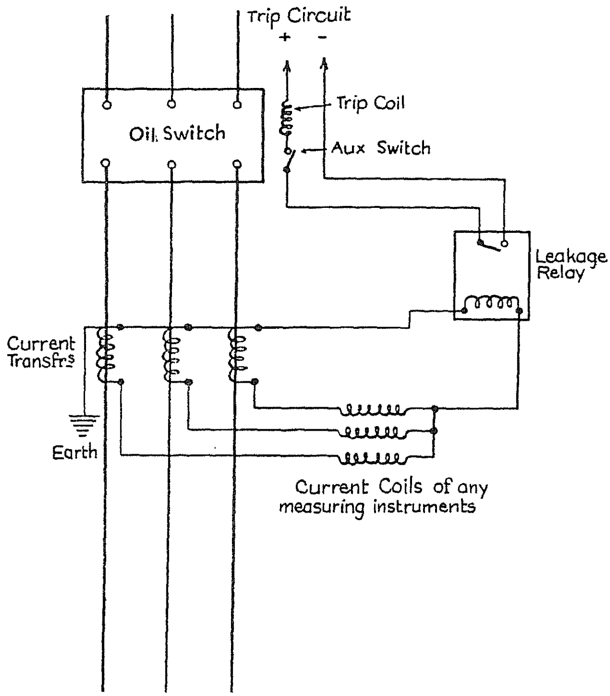


Fig. 28.—Core Balance Feeder Protection

Numerous modifications of this scheme of protection have been worked up to meet special conditions. Possibly the one most deserving of notice herein is an arrangement for two parallel cables only, in which a single directional element is used in conjunction with an overload relay, the directional relay having two contacts, to trip either one or other of the feeder circuit-breakers.

Because operating conditions demand that a main feeder circuit-breaker shall open only when the feeder itself is defective or is endangered by the continuance of extreme overload, a protective system combining a high setting overload time-limit relay with a device to operate on leakage current may be considered ideal. A leakage relay presupposes that the neutral point of the system is connected in some way to earth, since otherwise the path for return of leakage current would not be complete.

The simplest form of leakage current protection is the core balance system shown in fig. 28. A series transformer is connected in each phase of the feeder, and the secondaries are all connected in parallel. Under healthy conditions, and with a balanced load, the vector sum of all three currents will be zero, and no current will pass through the leakage relay.

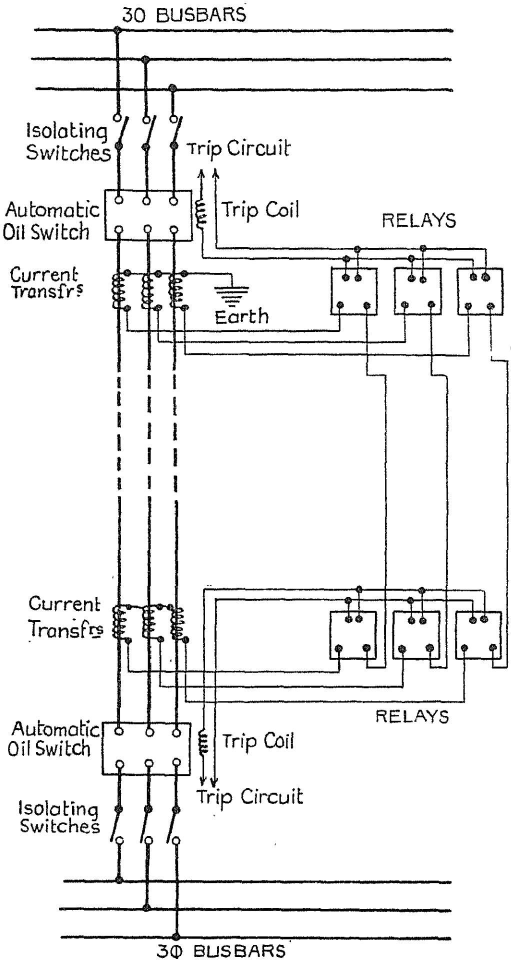


Fig. 29.—Balanced Voltage Feeder Protection

If the insulation of one lead proves defective, a leakage current will circulate, destroying the balance between the three secondary currents, and operating the leakage trip. The arrangement is capable of very fine setting, but is only applicable to single feeders. With feeders which are connected in parallel at both ends, the leakage current will pass through all conductors in parallel and thus open the circuit-breakers on healthy feeders as well as those on the faulty one.

In the Merz - Price (balanced voltage) system for feeder protection (fig. 29), the currents at the two ends of each feeder are balanced one against the other. In the event of a fault to earth on any conductor, the current flowing in will exceed that delivered at the far end. Pilot wires are run between series transformers located at the ends of the feeder, and relays connected so as to trip both circuit-breakers simultaneously. Such an arrangement operates only when the particular cable protected is defective, and in this direction is a distinct improvement on the scheme previously described.

It should be noted that normally no current flows in the pilot wires, the secondary voltages being balanced against each other.

The protective transformers must be specially designed and balanced for each particular circuit, and, for reasonable trip values on long feeders, become quite large. The necessity for running three pilot wires the whole length

of every three-phase circuit protected is a serious drawback, on account of the heavy initial cost.

A further limitation on long feeders was that the charging current in the pilot wires established a sufficient out-of-balance to trip the circuit-breakers, unless the relays were set for an undesirably high leakage current. Mr. Beard has recently introduced a sheathed pilot cable by the use of which this trouble is completely overcome.

In the split conductor (Merz-Hunter) system (fig. 30) each phase of a feeder is built up of two conductors of precisely equal resistance, in parallel. It is assumed that in the case of a fault to earth, one of the pair will carry more fault current than the other. This assumption has been proved correct during some years of wide practical application. The currents in the two half conductors are balanced one against the other, so that in the event of a lack of balance, a relay is operated to trip the circuit-breaker.

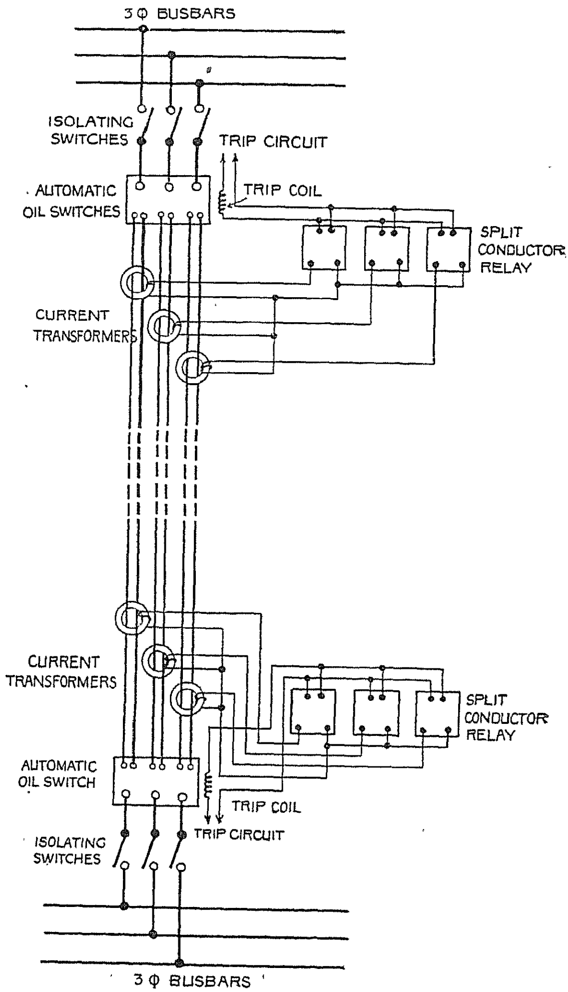


Fig. 30.—Split-conductor Feeder Protection

The usual method of accomplishing the balance is to take both halves of a phase through a special series transformer having two normally opposing primary windings. Under healthy conditions no current will be induced in the secondary winding of this transformer. With any unbalance, a secondary current proportional to the difference between the primary currents will energize the trip relay.

If the fault be approximately half-way between the transformers, they will both be affected by the out-of-balance, but it will be clear that with a fault close to one end, the transformer at that end will have a much greater out-of-balance than the remote transformer, which supplies current through two paths of practically equal resistance. To prevent the possibility of one

circuit-breaker failing to open under this condition, split contact circuit-breakers are employed. The opening of one circuit-breaker then throws maximum out-of-balance on the remote protective transformer and enables it to trip its circuit-breaker.

Using split contact circuit-breakers it is possible to employ bar primary protective transformers in all cases, a great advantage from the standardization point of view.

No pilot wires are needed, and the special split conductor is not much more expensive than a standard cable, since only slight insulation is required between the splits.

This system of protection has been applied to overhead lines up to about 20,000 volts, and there seems to be no technical reason why it should not be used for systems at any pressure.

In some cases split conductor protection has been applied to existing tie feeders run in duplicate, the two separate feeders being treated as the halves of a split arrangement. Where the cables have been of slightly different length and resistance, a low ohmic resistance has been used in series with one, and balance has been successfully obtained in that way.

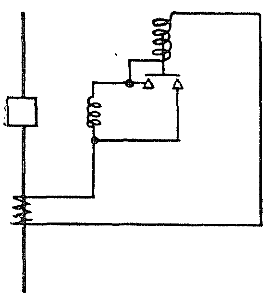


Fig. 31.—Series Trip Relay

The source of power used to energize the trip coils of circuit-breakers should be absolutely reliable. The practice of utilizing the secondary of a potential transformer which is connected across the generating station bus-bars is bad, in that a severe short-circuit will result in a loss of voltage at the instant it is most necessary.

Overload relays can be arranged for series tripping (fig. 31). In this case the relay contacts normally short-circuit the trip coil, which is otherwise in series with the current transformer and relay coil. When operating, the relay removes the short-circuit, and the current from the series transformer is enabled to trip the circuit-breaker.

Such an arrangement is not possible when using reverse power or leakage relays, since a sufficient current value may not be available.

By far the most satisfactory method is to furnish a small secondary battery with, if necessary, a motor-generator to keep the battery fully charged at all times. In many cases this battery will have other uses also, such as providing power for switch closing magnets, for emergency lighting in the event of the station being entirely shut down, and as a stand-by for excitation when starting a station from a standstill.

Although treated here under the general head of " Protective Systems ", the question of insulated versus earthed neutral is much wider, and in a measure affects all connected apparatus.

On a perfectly insulated three-phase system, with insulated neutral, the potential difference from any line to ground is equal to the phase-to-phase voltage divided by $\sqrt{3}$. The position of the earth potential point is unstable,

however, and varies with the relative condition of insulation on the three phases. Thus if one conductor is connected solidly to earth, the other two will be at a potential difference from earth equal to the full phase-to-phase voltage.

With the neutral point of the three-phase system earthed, a definite limit is placed on the potential stress which can be imposed on any conductor, this limit being the phase-to-phase voltage divided by $\sqrt{3}$. It follows then that a set of three single-phase transformers, which are so insulated as only to be good for a given phase-to-phase voltage when connected in delta on a system with insulated neutral, may equally safely be connected in star, giving 1·73 times the phase-to-phase voltage, if the neutral point of the star be earthed. To put it another way, if the neutral point be earthed, only $\frac{1}{1\cdot73}$ times the insulation would be required, which, on high-voltage work, represents a considerable economy.

On the other hand, continuity of service may be served better by connecting single-phase transformers in delta, since a defective transformer unit may be removed, leaving the other two connected in open delta, or V. The voltage relations are not affected in so doing, and only the capacity of the transformer bank reduced. If the single-phase transformers were star connected the only thing in emergency is to replace the defective unit with a spare.

A further advantage urged for transmission with an insulated neutral is that, in the event of insulator trouble, it is possible to earth that phase until repairs are effected, supply being maintained meanwhile. Moreover, the repair work can be carried out with the line in service. When this is done, there is every possibility that some of the line current in the earthed phase will pass through earth, resulting in telephone interference.

If the neutral point is not definitely fixed in relation to the lines, the failure of an insulator which sets up an arcing ground will cause transient voltage surges, resulting in insulator failures throughout the system.

The trend of opinion is clearly evidenced by the fact that within the last five years at least six of the power-supply authorities in the United States have changed their high voltage transmission systems from being fully insulated to earthed neutral. No case of a system changing from earthed neutral to fully insulated can be traced. Of the principal high voltage transmission systems in the world to-day, approximately 53 per cent have the neutral point dead earthed, 12 per cent are earthed through a resistance, and 35 per cent work fully insulated.

The fact has already been brought out, that many of the most desirable discriminating systems can only operate to full advantage if the neutral be earthed.

Modern practice strongly inclines towards earthing the neutral point of all three-phase systems. It is essential that the earth connection be of low and permanent resistance. The obvious point, the water-supply to a hydraulic station, is not always satisfactory, the water resistance varying widely in

different localities, besides which a rocky stream channel may conceivably be practically an insulator.

When an artificial earthing point has to be made, connection should be made at two separate points, and the resistance between these measured periodically as a check on their ground resistance. A resistance of 1·5 to 2·0 ohms per earth point may be considered reasonable. The earth contact may take the form of an iron pipe, driven 12 ft. or more into the ground, or it may be made with an iron plate, cast with projecting spikes, so as to increase the contact surface as much as possible. This cast plate is buried deeply in a place known to be permanently damp, often in soil especially prepared to ensure this condition. In all cases care must be taken to keep junctions between dissimilar metals out of contact with the soil, so as to avoid the risk of electrolysis.

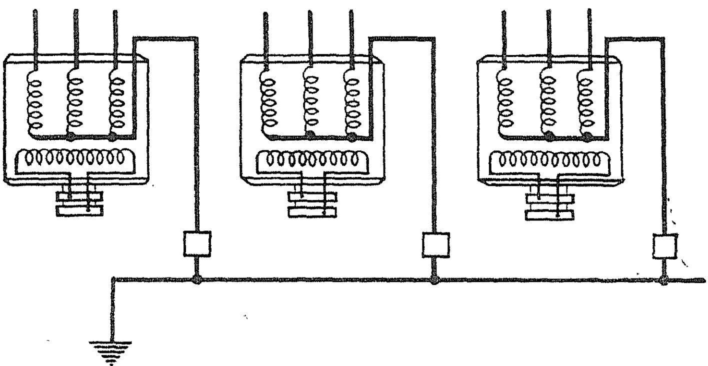


Fig. 32.—Neutral Earth Bus-bar

In a power station the neutral point of one generator only should be earthed. This has the double advantage of preventing any chance of circulating currents between machines, and of limiting the value of leakage or earth current to the capacity of one machine.

Earthing connections should be made through an oil switch of the hand-operated type. When an earth bus-bar is run, as in fig. 32, it will be desirable to arrange a simple interlock, so as to prevent more than one switch being closed at a time.

Another method of arranging the earth circuit is to use a single oil switch, together with double-throw isolating switches connecting to each generator neutral, as in fig. 33. With this it is impossible to connect more than one machine at a time to earth. It is not quite so convenient to operate as the more usual earth bus scheme.

It is usual definitely to limit the leakage current by inserting a resistance in the connection between neutral and earth. The value of this resistance determines the degree of protection afforded by automatic leakage devices. It is usually stated that the resistance must be so low as to enable it to pass the leakage trip current on the largest feeder, when line to star voltage is

impressed across it. The following consideration will show the defect in this idea.

The effect in the case of generator balanced current protection is interesting. For example, assume the machine shown in fig. 34, with the current balance relays set to operate with 50 amp. out-of-balance across

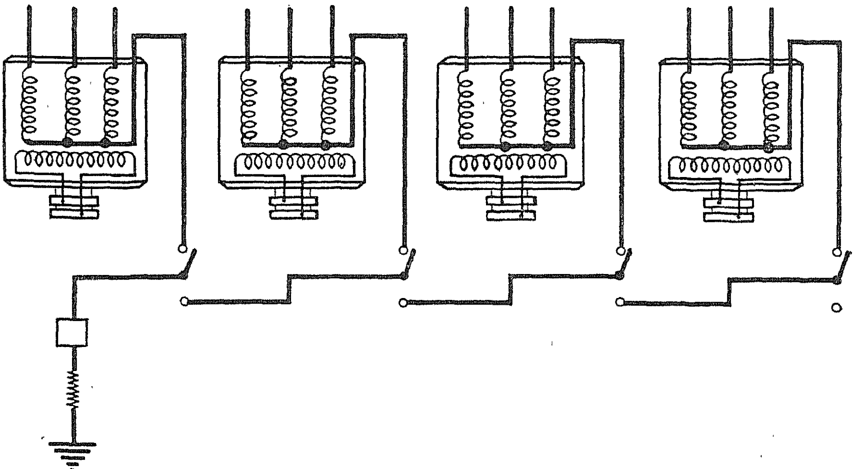


Fig. 33.—Neutral Earth Selector Switches

the winding. If a fault to earth develops at the machine terminal A, the full-phase voltage is impressed across the resistance, which, to pass 50 amp., can have a value of $\frac{1000}{50} = 20$ ohms. Suppose the fault occurs at B, half-way along the phase winding, then only half the phase voltage will be impressed across the resistance, which must not exceed 10 ohms if the circuit-breaker is to be tripped. Similarly if the fault be at C, only 5 per cent of the distance from the neutral point, the limiting resistance would not have to exceed 1 ohm.

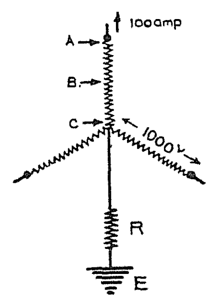


Fig. 34

It is thus clear that the value of neutral resistance must be fixed by the degree of protection desired for the generator, and not only from considerations of feeder size.

3. Use of Reactances.—If a feeder short-circuit occurs close up to the generating station bus-bars, the supply voltage to the whole system will be affected. The pressure may quite easily fall so low as to cause all connected synchronous machinery to drop out of step, especially if the feeder has time-limit automatic protection. With a small plant such interruptions must usually be tolerated, since the capital cost cannot be increased sufficiently to purchase more elaborate equipment.

With large power-supply systems the effects of such interruptions are

proportionately more widely spread, and may be felt by whole communities. Cessation of supply in industrial districts, even if only for a few minutes, represents a large amount of money, and it is conceivable that a single shut-down may cost more than an apparatus capable of preventing the trouble. On the trunk feeders from a big power station continuity of supply is of first importance. More chances may reasonably be taken on feeders radiating from substations.

If all the generating plant in a station be connected to a single set of bus-bars, extremely heavy currents will pass in the event of short-circuit. In a hydraulic station of 100,000 k.v.a. capacity, generating at 6600 volts, three-phase, the aggregate current with a symmetrical short-circuit and a machine reactance of 20 per cent will amount to approximately 44,000 amp. in the first cycle. All oil circuit-breakers on circuits connected directly to the bus-bar system must be capable of interrupting this current, or a somewhat smaller amount according to their opening time delay. The cost and bulk of an oil circuit-breaker are roughly proportional to the short-circuit current which it can interrupt, so that the capital cost per circuit of switchgear is greatly increased in large plants arranged in this way.

A further important point affected by the magnitude of the short-circuit current is the bracing of conductors. The mutual repulsion between conductors varies as the square of the current, and inversely as the distance between their centres.

The curves of fig. 35 show the repulsive forces between three conductors lying in the same plane. As the currents concerned are the instantaneous peak values, it will be seen that great precautions are needed to prevent conductors breaking from their supports. Such occurrences are by no means uncommon, and in some of the large steam stations of America feeder cables even have been known to burst their paper and lead sheathing.

A few years ago designers of large generators were much troubled by the movement of stator windings under the influence of short-circuit currents, and in some cases reactances were installed to limit the current. The art of bracing the windings is now well understood, and, even on modern steam turbo-alternators having low reactance, no trouble is experienced. A small external reactance is still often desirable on high-voltage machines, which have two or more conductors per slot, to prevent piling up of voltage on the end turns under abnormal conditions.

It will be seen that reactances may be installed for two distinct reasons, firstly, to localize the effects of operating troubles, and secondly, to protect connected apparatus.

It is not impossible either to build oil circuit-breakers to rupture, or so to brace conductors as to withstand, any current, but all considerations point to the desirability of reducing the short-circuit current, and particularly of confining the effects of short-circuit as closely as possible.

There are four general methods for the employment of separate reactances, each of which has its own special field. These are:

1. In generator circuit. Fig. 39.
2. In feeder circuit. Fig. 38.
3. Sectionalizing the main bus-bars. Fig. 40.
4. Between generators and a synchronizing bus-bar. Fig. 42.

In order better to illustrate the effect of reactances in these various positions, reference will be made to an assumed plant having as units three-phase, 6600 volt, 10,000 k.v.a. water-wheel alternators with an instantaneous

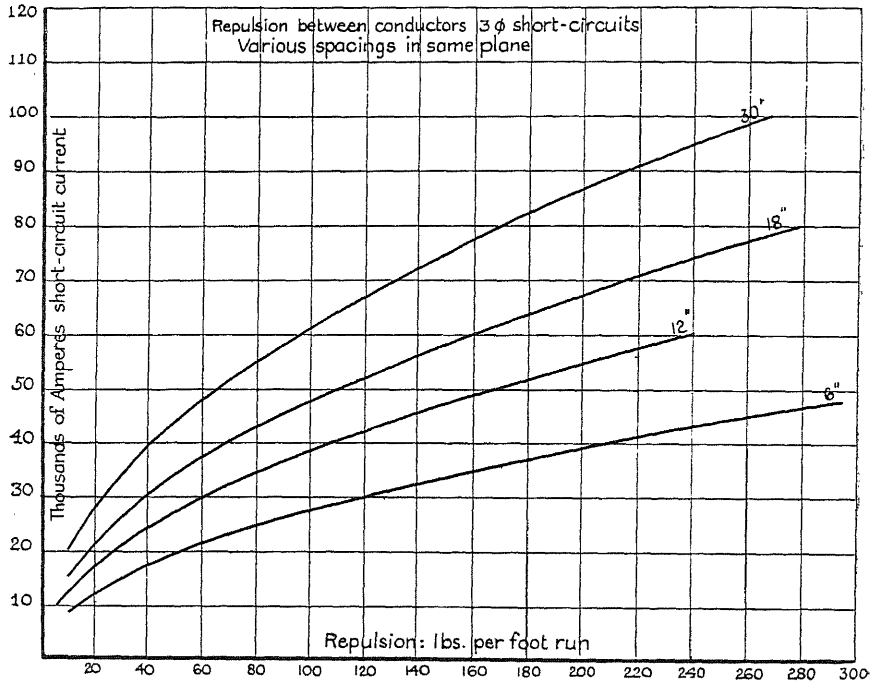


Fig. 35.—Mutual Repulsion between Conductors carrying Heavy Currents

reactance of 20 per cent. The feeders will be taken as for 10,000 k.v.a. normal load each.

It should here be explained that separate reactance coils are customarily rated by the voltage drop across their terminals at some stated load, the voltage being expressed as a percentage of the single-phase system voltage. Thus a 5 per cent, 10,000 k.v.a. reactance on the assumed 6600-volt system would be one which caused a drop of 190·5 volts when carrying a load of 10,000 k.v.a., 190·5 volts being 5 per cent of 3810 volts, which is the pressure from any one phase to the neutral point.

Figs. 36 and 37 show the current values in a feeder short-circuit when reactances of various sizes are inserted in each of the four typical positions. Cases with three and five generating units are taken, the better to show the value of bus reactance.

It will be noted that when considering feeder short-circuit, reactance in the feeder itself, as in fig. 38, is most effective. The smaller the feeder, the more marked does this become; see the curve for a 2000-k.v.a. feeder on fig. 36. Feeder reactance localizes the effects of trouble, confining them to the single feeder on which is the short-circuit. To obtain a given degree

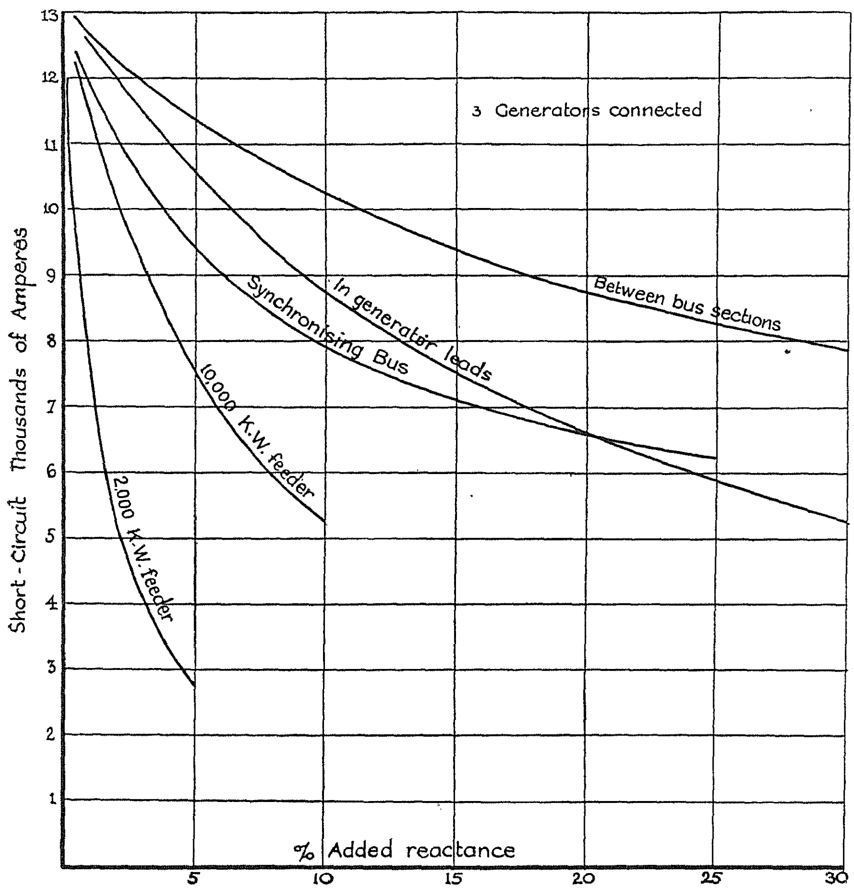


Fig. 36.—Effects of added Reactance in various points: three generators

of protection, i.e. to limit the current on short-circuit to a definite figure, less reactance is required in the feeder than elsewhere.

When used, feeder reactances are generally of the order of from 3 per cent to 5 per cent, based on the normal rating of the feeder.

This scheme offers no protection when a short-circuit occurs on the bus-bars, or in a generator winding. In such a case the current is unlimited, and the bus-bar voltage falls to zero, causing synchronous apparatus to drop out of step.

If reactance is put in series with each generator, as in fig. 39, the

current is limited, no matter where the short-circuit may be. In the event of a generator short-circuit, the reactance in series with that machine will act in the same way as a feeder reactance, and will limit greatly the current which the healthy machines can feed into the fault.

The protection afforded in case of a feeder short-circuit is less than with

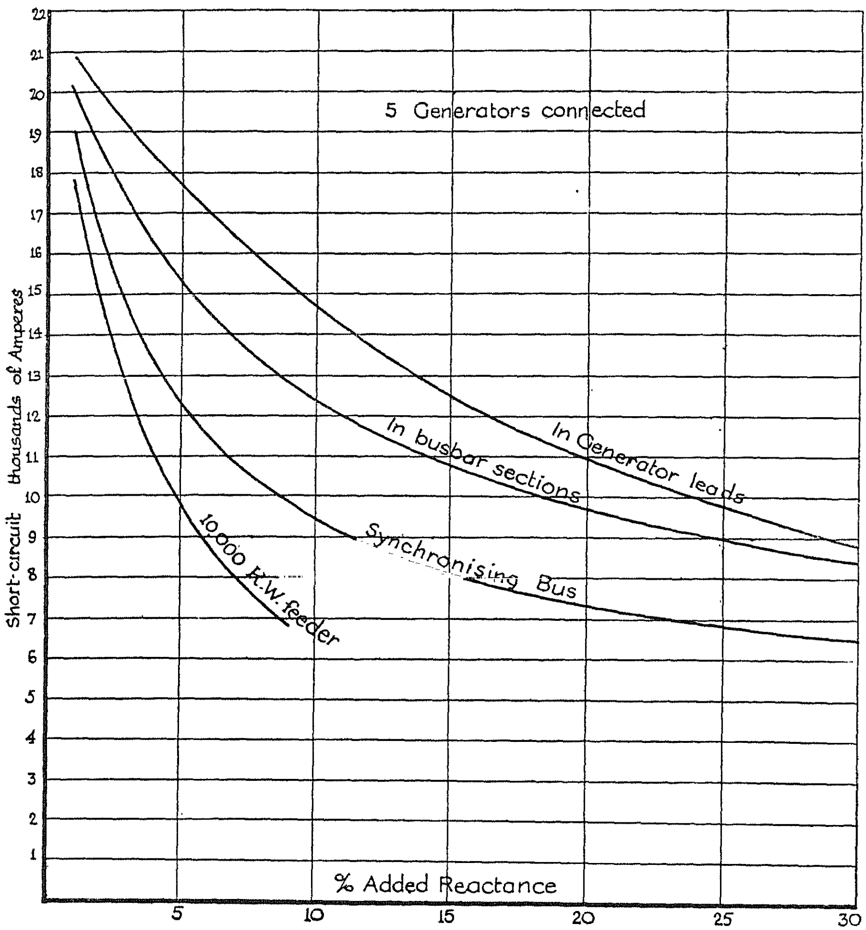


Fig. 37.—Effect of added Reactance in various points: five generators

feeder reactance, the whole system being affected by any drop in voltage. As a rule generator reactance is only used with high-voltage machines or in series with old generators, with the object of protecting the windings from excessive mechanical shock. In such cases the reactance may be from 5 per cent to 10 per cent.

In both these cases the current normally passes through the reactance, involving not only the losses in the reactance, but also a varying voltage drop according to the load.

With reactances in the run of bus-bar between generators (fig. 40), only as much current passes from one section to the other as is necessary to equalize the loading of the generators. Thus losses are reduced, and voltage regulation is improved. The greater the number of generators, the better the protection afforded in event of either a feeder, generator, or bus-bar short-circuit. The effects of a short-circuit are largely confined to those circuits supplied from the bus section to which is connected the feeder in trouble.

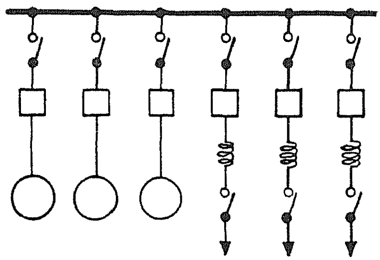


Fig. 38.—Feeder Reactance

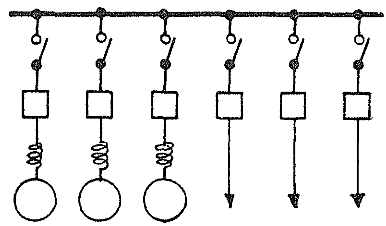


Fig. 39.—Generator Reactance

There is a definite drop in voltage and a difference in phase angle between two bus sections separated in this way, which may become appreciable between the extreme ends of a large system. If any generator unit is out of service, the corresponding feeders can only be supplied through adjacent reactances.

In certain cases the bus-bar reactance is arranged to be short-circuited normally, as shown in fig. 41. The short-circuiting switch is operated by a discriminating relay, so that in the event of trouble it will open first and introduce the reactance before any other circuit-breaker operates to open the circuit.

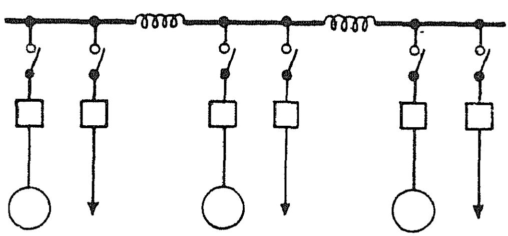


Fig. 40.—Bus-bar Reactance

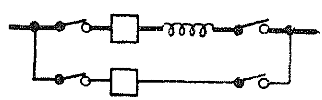


Fig. 41.—Reactance Short-circuiting Switch

This arrangement is of benefit only in reducing the duty imposed on the circuit-breakers, and does not limit the mechanical stresses thrown on conductors and supports.

As bus-bar reactances do not normally carry much current, they are frequently as great as 25 per cent, based on the capacity of one generator. The bus-bar reactance arrangement is probably more extensively used than any other, often by itself, but sometimes in conjunction with individual or group feeder reactances.

Opinions are somewhat divided as to the size of generator groups which

should be separated by reactance. The majority of operators appear to prefer groups not greater than 40,000 to 50,000 k.v.a., some going so low as 20,000 k.v.a.

The use of reactance between each generator and a separate synchronizing bus (fig. 42) was first suggested by the late Mr. Stott, and is dealt with in considerable detail in a paper before the American I. E. E. ("Theoretical Investigation of Electric Transmission Systems under Short-circuit Conditions", I. W. Gross, *Trans. A. I. E. E.*, 1915).

With this arrangement each generator normally serves its own group of feeders. In the event of feeder or bus-bar short-circuit, however, only that generator which is directly connected supplies current unlimited by reactance. The current from all other machines is limited, first by their own synchronizing reactances, and secondly and collectively by the synchronizing reactance connecting to the section of bus-bar in trouble. With an increasing number of generating units this scheme improves in its ability to limit the total short-circuit current. There is further advantage in the fact that all generators except the one directly connected are equally overloaded in case of short-circuit, instead of throwing the bulk of the load on to the neighbouring sets, as is the case when using bus section reactances. The value of reactance used in the synchronizing bus is generally about 3 per cent.

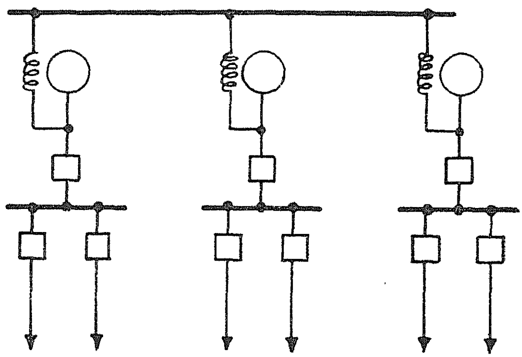


Fig. 42.—Synchronizing Bus-bar Reactance

This scheme has not been adopted to any extent in Great Britain. In the one or two instances where it is used, ease of application to an existing switchgear installation appears to have played an important part.

The last two schemes described have the advantage of definitely limiting the interchange of current between generators in the event of faulty synchronizing. In a large plant with skilled operators, the chances of defective operation in this way are small, but the magnitude of possible current in the worst case makes the advantage a definite one.

It has been pointed out that in a water-wheel station it is possible for added reactance between generators to reduce the synchronizing stability of the machines, under conditions where the load is subject to large and sudden fluctuations. The experience of numerous hydro-electric stations goes to show that this is a condition from which serious results need not be anticipated in practice. Reference should be made to the original paper, "Reactors in Hydro-electric Stations", J. A. Johnson, *Trans. A. I. E. E.*, 1917.

"There are two types of reactance, the iron-clad type and the air-core type. The former consists of a choke coil with an iron core similar to a

standard transformer but with a large air-gap, or a number of small air-gaps interposed in the path of the magnetic flux.

"The air-core type consists simply of a plain coil in air, the inductance of which is designed to give the required choking effect without the use of an iron core. Such coils are usually supported on concrete frames either cast in or built up, or on porcelain mountings.

"Either type can be built to give satisfactory service. The choice depends mainly on:

"1. The type of service obtaining.
"2. The location and space available.

"1. As regards the type of service, the choice reduces itself largely to a question of capital cost; the relative prices depend on the short-circuit current required in terms of the normal current, i.e. the maximum current up to which a straight line volt-ampere characteristic is required.

"As was indicated previously, bus-bar reactances are commonly of the order of 20 per cent to 25 per cent, so that they limit the maximum current flow to five or four times their normal current rating.

"Generator reactance will rarely exceed 5 per cent, whether connected in series or through a synchronizing bus. Similarly feeder reactances are generally about 5 per cent. This means that the maximum currents may be 20 times normal current or even more.

"In each case the volt-ampere characteristic must be approximately a straight line up to the limiting current. This is inherently attained with the air-core type, but considerably influences the design of the ironclad type.

"Owing to the heavy magnetic fields resulting from the large short-circuit currents, the iron sections in the ironclad type must be greater the higher the limiting current. The result of this is that the cost of such reactances increases with the value of the current limitation for a given normal current. This consideration does not arise in the air-core type, but in point of cost the ironclad type can be designed to compare favourably with the air-core type up to limiting currents of about eight times normal.

"2. The location of the reactances with regard to structural or other iron and steel work and electro-magnetic instruments is of considerable importance. In this respect the iron-clad type has the advantage over the air-core type in that there is no stray field.

"Iron-clad reactances can be installed in any location where the installation of the air-core type would give rise to disturbance of balance and possible heating trouble in adjacent ironwork. To mitigate these effects air-core reactances should be so installed that there is no ironwork nearer than a distance approximately equal to the overall diameter of the coil.

"This is often an important factor where the space available is limited, as is generally the case in older stations where extensions necessitate the use of such apparatus. If sufficient space is available, as may be provided when laying out new stations, the air-core type can be installed without possibility of trouble in this direction. It has less liability to fire risk.

"The iron-clad type is totally enclosed and the tank can be earthed, whereas the air-core type is mounted on insulating supports and the coils are usually exposed at full-line voltage, unless completely protected by concrete or porcelain frames."*

For the purpose of preliminary estimates of space, the following tables of approximate over-all dimensions of single-phase iron-clad and air-core reactances are given. When applying these, particular attention should be paid to the notes on location previously given.

TABLE I.—IRON-CLAD REACTANCES, 6600 VOLTS

3-Phase Circuit K.V.A.	25 per cent Reactance. Approximate Dimensions in Inches.			5 per cent Reactance. Approximate Dimensions in Inches.		
	Length.	Breadth.	Height.	Length.	Breadth.	Height.
30,000	84	72	76	74	60	86
20,000	74	60	72	60	45	96
10,000	60	45	84	60	45	84
5,000	60	45	72	48	36	84

TABLE II.—AIR-CORE REACTANCES, 6600 VOLTS

3-Phase Circuit K.V.A.	25 per cent Reactance. Approximate Dimensions in Inches.		5 per cent Reactance. Approximate Dimensions in Inches.	
	Diameter.	Height.	Diameter.	Height.
30,000	64	90	45	59
20,000	55	75	40	53
10,000	50	66	32	43
5,000	45	56	30	40

*Extracted from "Large Power Transformers", A. G. Ellis and J. L. Thompson, *Trans. I. E. E.*, Vol. LVII, August, 1919.

CHAPTER VIII

Excitation Systems; Switchgear; &c.

Excitation systems; voltage regulators; design and selection of oil circuit-breakers

1. Excitation Systems.—The form of exciter to be adopted depends very largely upon the character of the hydraulic development. In a high-head or medium-head plant, where the water-wheels are probably of fairly high speed, direct-driven exciters will be found an economical and workable proposition.

Slow-speed exciters would be expensive, and moreover do not respond quickly to the action of automatic voltage regulators, which in such case are themselves expensive on account of the relatively large currents to be handled. Hence in a low-head plant it is frequently advantageous to employ exciters which are separately driven. In most such cases a separate exciter for each generator is unnecessary, although in the Keokuk station of the Mississippi River Power Co. it is done. Usually all generators are excited from a single machine. Provided all generators are required to give the same bus-bar voltage at all times, this is satisfactory, since the automatic voltage regulator operates on the exciter shunt field.

In those stations where the system may be split up electrically, and where in consequence it may be desired for one generator to work independently of another, individual exciter sets are essential, whether these be direct driven or separately motor driven.

Custom demands an alternative source of excitation in practically all cases. It is somewhat difficult to account for this, since the D.C. generator is one of the oldest and most reliable pieces of electrical apparatus. There is a sound argument for having a battery stand-by capable of carrying the excitation for short periods, since in a total shut-down of the station such a scheme would facilitate a quick restart. It would be connected in the place of the spare exciter shown in fig. 1.

Also where separately driven exciters are used, spare units are necessary, because the failure of a single exciter machine might involve shutting down the whole station until repairs are effected.

Considering first the high-speed plants with direct-driven exciters only, it will be found that the complete cost of the excitation equipment is low, as the cable work and switchgear is reduced to a minimum. The arrange-

ment lends itself to automatic voltage control on separate generators, but it must be borne in mind that variations in the alternator load, which also affect the speed of the prime mover, will correspondingly alter the excitation. Unless automatic voltage regulators are used, the voltage control will be inferior to that obtained with separate excitation.

In a large Californian station, recently started, there is no stand-by source of excitation, but a complete spare exciter is kept. In the event of the direct connected exciter of any generator failing, it will be removed, and the spare exciter unit mounted in its place. This same arrangement is used in the new Queenston station of the Hydro-electric Power Commission of Ontario. This practice is consistent with that adopted for other items

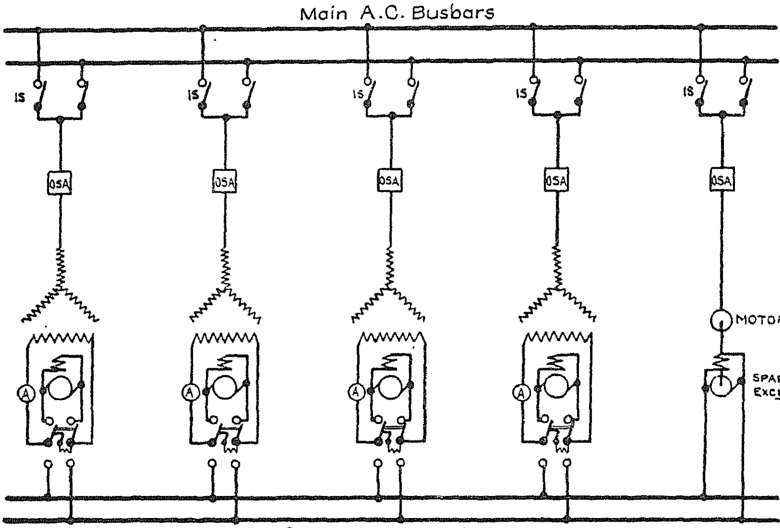


Fig. 1

of station equipment, as, for instance, carrying one spare single-phase transformer unit to replace one leg on any of several banks of transformers.

In general practice, however, to provide for the failure of an exciter, a spare motor-driven machine of sufficient capacity to excite the largest alternator may be installed. Rotary converters are unsuitable since voltage variations on the A.C. side are reflected in the D.C. supply. In a plant having many generating units the motor may draw its supply from the main bus-bars. In a station having few units, but forming part of a large power system, supply to the station service transformers is frequently more reliable, as these transformers will be arranged for connection to bus-bars or incoming circuits at will.

In any case bus-bars should be run from the spare exciter through the length of the station. From these, taps are taken to an exciter panel beside each generator, on which is a double-throw switch, with discharge resistance contacts, so that the field may be thrown readily on to the spare exciter.

Arrangements have to be made so that the voltage regulator for any generator also can be thrown on to the stand-by exciter set. The arrangement is shown diagrammatically in fig. 1.

This arrangement of separate exciter panels close to each generator is usually the most economical of copper, although if preferred all panels may be grouped together into one switchboard.

An alternative arrangement, shown in fig. 2, is well suited to an isolated station of few units. In this each direct-driven exciter is of sufficient capacity to serve two alternators. A simple arrangement of switches then serves to parallel two fields and to cut out one exciter when necessary.

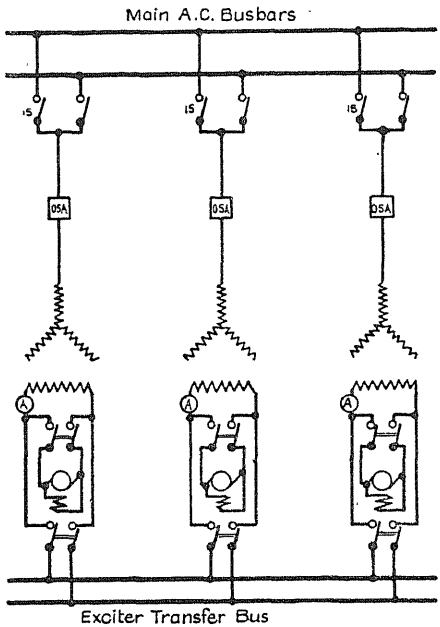


Fig. 2

When separate exciters are used, at least two machines should be provided, in which case either should be large enough to supply excitation for the whole power station. If three exciter units of equal size are provided, then one should be a stand-by.

The exciter sets should be driven by different means if at all possible, the chances of two sources of power failing simultaneously being very remote. For instance, one set may be driven by a small water-wheel, and the other be driven by a motor from the station service supply. It is desirable to keep both normally running at half load, so that alternative supply is always instantly available.

A similar effect is obtained by the Ontario Power Co., in their station at Niagara Falls, where the generator which drives the individual motor-driven exciters is itself driven by a water-wheel, and by a motor on the same shaft. The motor normally "floats" on the station bus-bars, and would instantly take charge should the water-wheel fail.

While the water-wheel-driven set is ideal in that it is not affected by conditions of load, or by the operation of other parts of the station equipment, it is also the most expensive. The station building must usually be extended to provide room for the water-wheel and penstock, which are themselves more expensive than a motor would be.

In a plant which is well sectionalized, both exciters may be motor-driven, the motors being supplied from separated sections of the bus system, which are unlikely to be affected by the same disturbance.

The separate excitation system should serve two distinct sets of exciter

bus-bars, corresponding to the different prime movers, after the manner shown in fig. 3. Each alternator field will then have a double-throw field-breaking switch, so that it may be connected to either set of bus-bars. If the exciters were paralleled, trouble on one would affect the other. By making separate systems, however, those fields connected to the exciter in trouble can be thrown over instantly on to the sound exciter bus-bar.

Generally speaking, automatic protection is not permissible anywhere in the exciter circuits, save in connection with "field killing" protection of the generator. The field ammeters, and exciter ammeters and voltmeters are usually so mounted as to be directly before the switchboard operator, who must make manually any necessary changes in connections. The

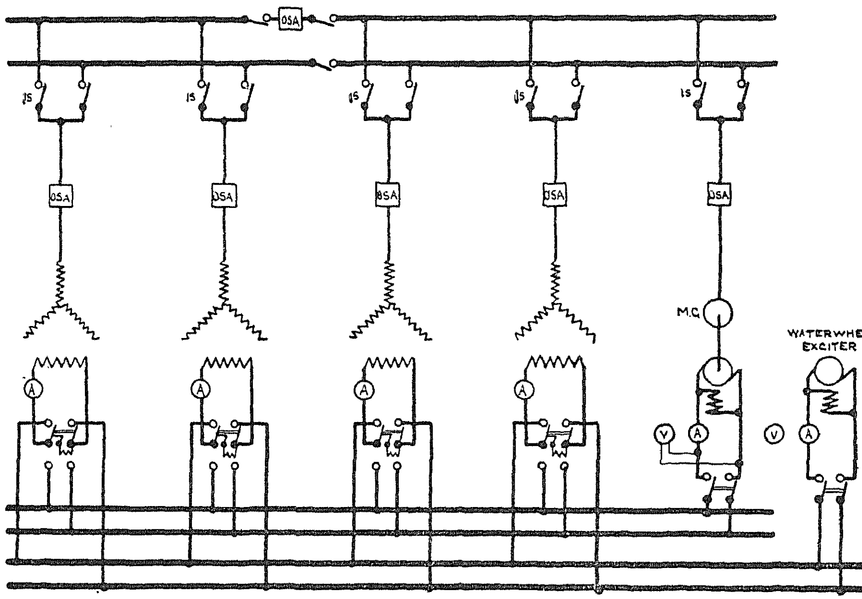


Fig. 3

change-over switches are preferably electrically operated from the main control switchboard.

It is undesirable that the exciters should be used to supply direct current for any other purpose, such as for the operation of oil switch closing coils, &c., since the exciter voltage is liable to variation where voltage regulators are used. To avoid risk of trouble the connections in the exciter system must be kept as simple as possible.

2. Automatic Voltage Regulators.—Few large plants, either steam or hydraulic, are to-day considered complete without the installation of automatic voltage regulators on the generators. This is particularly the case in hydraulic stations, where the feeders are usually of large capacity. The loss of one of these, through operation of the circuit-breaker, would cause serious voltage fluctuation. Automatic regulators may operate to keep

a constant bus-bar voltage, or to keep constant the voltage at some distant point, irrespective of the current. Alternatively, they may be arranged so to control the machine excitation as to cause the bus-bar voltage to increase with an increase of load, thus providing in a general way for line drop in the feeders.

In long-distance transmission schemes, where the generators are all tied to a common bus-bar at the power station, the voltage variation may differ on various feeders. In such a case it is most usual to control for a constant generating bus-bar voltage and take care of the sub-station pressure by means of regulating transformers at each point independently.

It is proposed to give a brief account of the broad principles on which automatic voltage regulators work, and thereafter a description of the construction and operation of the principal forms of automatic regulator. In these descriptions only apparatus for the control of alternators will be dealt with. Similar apparatus in a simpler form is used for direct-current generators.

The instruments on the market may be divided into two general groups:

1. Those in which regulation is secured by short-circuiting a fixed portion of the field resistance for varying lengths of time.
2. Those in which a control magnet actuates a mechanism for moving a rheostat arm.

The earliest attempts at automatic regulation with instruments coming under group 1 may be represented by the elementary diagram (fig. 4). Such instruments were fairly successful with direct-current machines, but, for reasons which are explained later, they could not be applied in the same form to the regulation of alternators.

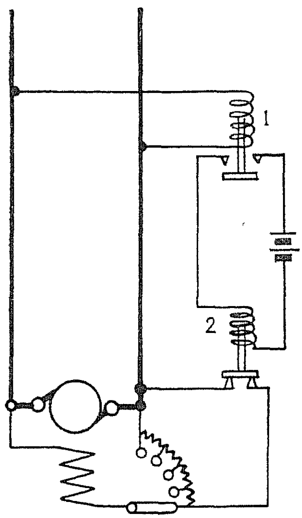


Fig. 4.—Elementary D.C. Regulator

It will be seen that there is a voltage coil (1) connected direct across the main terminals of the generator. In this coil there is an armature which, on rising, closes a pair of light contacts. When closed, these contacts excite a relay (2) carrying heavy contacts, which short-circuit the generator field rheostat when they are closed.

With a low line voltage the voltage coil is unable to hold its armature, and thus opens the circuit of the relay coil (2), allowing the relay contacts to short-circuit the field rheostat and causing the machine voltage to build up. With a high line voltage this action is reversed, the relay contacts opening and allowing the full rheostat resistance to take effect and thus reduce voltage.

In order that the machine voltage may respond quickly to the action of the automatic regulator, it is necessary to cut in or out of the field circuit

much more resistance than that required just to bring the voltage to normal pressure. In consequence, if such an instrument as is shown in fig. 4 were to operate sufficiently slowly, the resulting voltage would oscillate with regard to the desired normal voltage much as shown by the thin line in fig. 5.

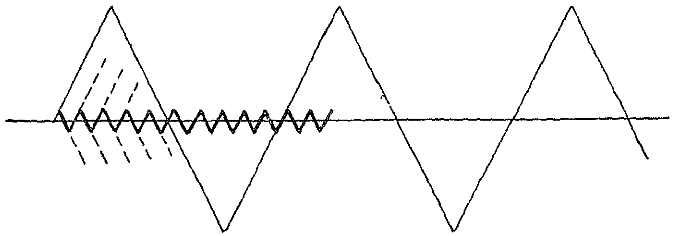


Fig. 5

The whole object in designing the automatic regulator is to make it so sensitive and quick in operation that the machine field never has an opportunity to build up or demagnetize to the full extent, and thus the oscillations in the voltage wave are reduced in amplitude and increased in frequency so that the curve becomes practically a straight line.

If an elementary regulator of this type were applied to an alternator it would be ineffective, due to hunting. This hunting is inherent in the regulation of an alternator, and is caused by the self-induction of the alternator field winding.

The elementary diagram in this case is shown in fig. 6. Consider the instant, as in the illustration, when the line pressure is below normal, the voltage coil contacts open, and the relay contacts short-circuiting the exciter field rheostat. The alternator voltage is in the act of building up.

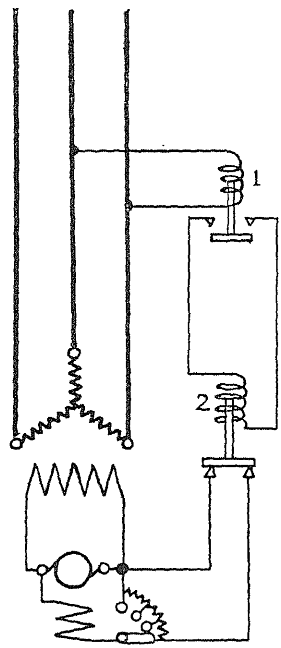


Fig. 6.—Elementary A.C. Regulator

The instant the line voltage attains its normal value, the relay coil (2) is excited and the relay contacts open, causing the exciter voltage to start to drop. The alternator voltage, however, does not cease to increase at this instant, since the exciter voltage is still above the value necessary to maintain normal generator voltage. That this is the case is evident when it is considered that, in the act of building up, the exciter has been supplying a voltage equal to the drop in the alternator field, plus the inductive drop or counter E.M.F. due to the increase of flux in the field winding. This latter value will depend on the rate at which the exciter builds up. Therefore, at the instant the alternator voltage becomes normal, the exciter voltage is in excess of the value necessary to maintain the normal line voltage by an amount equal to the inductive drop in the alternator field. The alternator voltage,

therefore, continues to increase for a time, even after the relay contacts have opened. By the time the alternator voltage has dropped to normal, the exciter voltage is then well below that required to maintain normal line voltage. The alternator voltage is, therefore, carried continually above and below its proper value; in other words, hunting takes place.

From the above it will be seen that the simple regulator sketched out above requires some additional element to bridge the alternator field inductance, and it is in the methods employed to do this that the regulators which work on the principle of short-circuiting the field resistance vary in construction and operation. The same effect of the inductance of the alternator

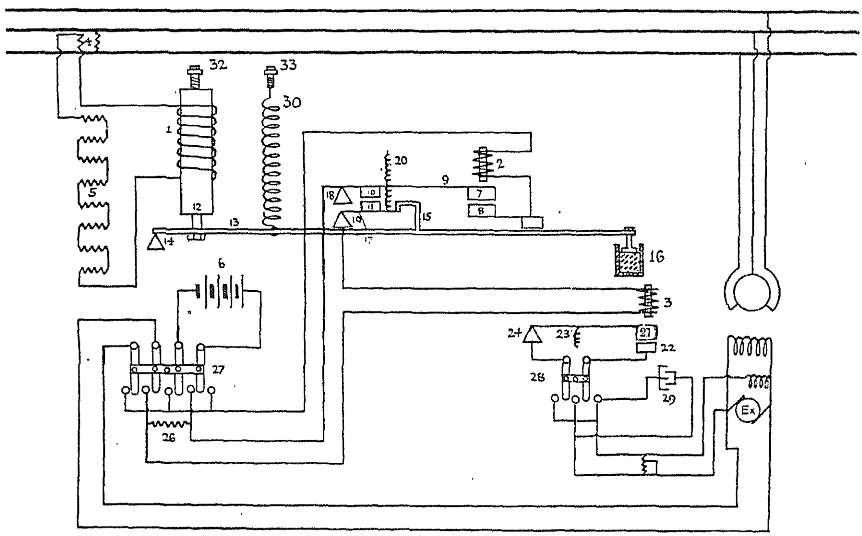


Fig. 8.—Simplified Diagram of Metropolitan-Vickers Regulator

field winding is operative in the case of regulators of the second type, and has to be considered.

Reference to the parts designed to meet this condition will be mentioned in the descriptions.

On modern machines the synchronising forces are usually so great that in a station including large and small generators the automatic regulator need only be applied to the larger sets, and the small sets allowed to trail.

As typical of regulators coming under the first group may be taken that made by the Metropolitan-Vickers Electrical Company (fig. 7). This instrument consists of the combination of a main control coil, vibrator coil, and a relay coil, the function of the vibrator coil being to transmit the line voltage variations to the relay coil circuit in such a manner as to obviate the hunting referred to in the foregoing general description of the regulators of this type.

Referring to fig. 8, the main control coil (1) is connected across the bus-bars of which the pressure is to be regulated. The vibrator coil (2) is

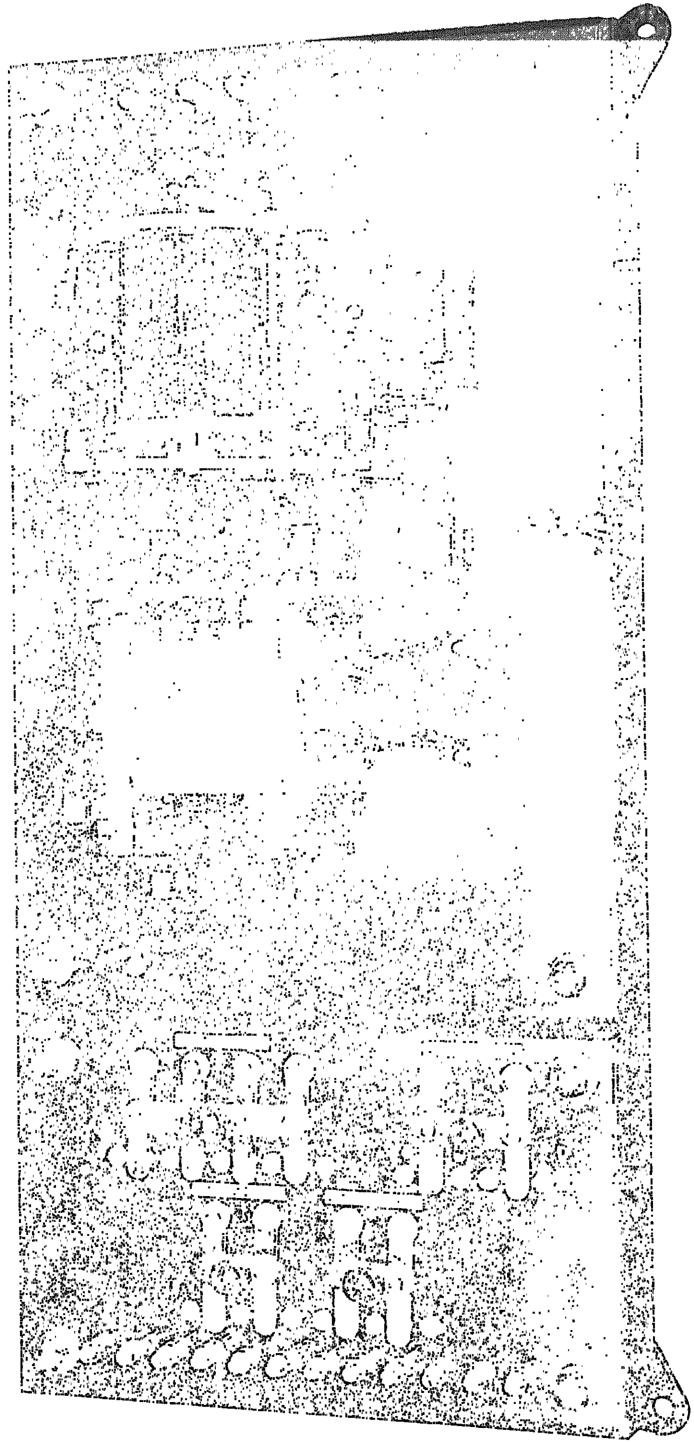


Fig. — Metropolitan Vickers Automatic

connected in series with a four-volt accumulator (6) through the contacts (7) and (8), so that its armature (9) is caused to vibrate at a constant amplitude and frequency.

The relay coil (3) is connected across the exciter through two co-operating contacts (10) and (11). Contact (10) is mounted on the armature of the vibrator magnet, while contact (11) is separately pivoted in such a way that, under the action of the spring (20), it tends to keep in touch with contact (10). These two contacts are not allowed to be permanently together. The time they are in contact compared with the time they are separated depends on the position of the stop (15), which is carried on the control coil armature.

The function of the relay is to actuate the main contacts (21) and (22) which are connected across the exciter shunt rheostat; (22) is fixed, while (21) is attached to the relay coil armature which is flexibly supported at (24), and to which a spring is fitted tending to keep the contacts (21) and (22) together. Contact is only made between these contacts when the relay is not excited.

The main coil (1) is fitted with a fixed pole and a moving core attached to the pivoted aluminium lever (13). The magnetic pull of the coil is supplemented by that of a spring (30). It is well known that with such an arrangement the magnetic pull of the coil, and that due to the tension of the spring, can be adjusted easily so that the arm will take up a higher or lower position with a very small variation in the magnetic pull of the coil. In this way slight variations of voltage give a new position of the aluminium arm (13). If we consider the position of this arm and stop (15) with relation to the contacts (10) and (11)—remembering that the upper contact (10) is continually vibrating over a certain distance—it is seen that if the stop (15) is in its extreme upper position, the contact (11) is free to follow and be in touch with contact (10) throughout the whole of its travel, while in the extreme lower position the contact (11) is prevented altogether from making contact with (10). In any intermediate position of this arm and stop (15) between the two extreme positions, there is a certain value of the $\frac{\text{time open}}{\text{time closed}}$ on the part of the contacts (10) and (11). This value may be anywhere between infinity and zero, which two figures correspond respectively to the extreme lower and upper positions of the arm (13).

As the contacts (10) and (11) control the relay coil (3), it is clear that the length of time that the relay magnet is excited depends on the position of the stop (15), which, being attached to the core of the main control magnet, changes its position in response to the changes in bus-bar voltage. Consequently, the length of time that the exciter field rheostat is periodically short-circuited depends finally on the position of the stop (15), and the length of time during which the exciter field resistance is in circuit will be varied accordingly.

With an increasing load, the voltage on the line would tend to fall, but with a fraction of 1 per cent drop in line voltage, the aluminium arm (13),

carrying stop (15), takes up a lower position, increasing the time the relay contacts short-circuit the exciter field rheostat. With a decreasing load the line voltage tends to rise, but an extremely small increase in the voltage causes a new position to be taken up by the arm (13), so reducing the time the relay contacts short-circuit the exciter field rheostat.

The arrangement so far described is that adopted to keep constant the bus-bar pressure. Should it be desired to cause the bus-bar voltage to increase with increase of load, this is accomplished by adding a compounding winding to the main control solenoid (1). Where the bus-bar system is such that totalizing current transformers can be installed, this arrangement is used to excite the compound winding, which is designed to operate so as to meet pre-determined conditions of voltage drop and load.

Occasionally a totalizing transformer is not feasible, and in this case series transformers in the leads of each generator are connected to a common compounding coil on the regulator.

When it is desired to retain some measure of ready control over the voltage, a small variable resistance is placed in series with the main voltage coil, or tappings may be brought from the compounding winding to a small multi-way switch. When two or more generating stations serve the same distributing system this facility of adjustment is often desirable, in preference to making mechanical adjustments, the results of which must be tried out on each occasion.

The combination of light parts moving quickly over extremely small distances renders this regulator sure and rapid in operation and free from hunting. The regulator itself can be adjusted easily, as the component parts operate independently of each other.

Provision is made for automatically recharging the small accumulator. The resistance (26) passes a current slightly in excess of that taken by the vibrator coil, at the average voltage of the exciter. To compensate for the variation of the exciter voltage between no load and full load on the alternator, the relay coil (3) is connected in parallel with the charging resistance (26), as the summation of the time it is in circuit is greater when the voltage is low and less when the exciter voltage is high. This secures a correct charging rate under all conditions of running of the alternator.

Reversing switches are provided for changing the direction of current through the various contacts, so as to ensure even wear. Condensers are connected across the main contacts to absorb the inductive voltage due to the variation of the field current of the exciter.

As the vibration of the contacts does not depend on the variation of the exciter voltage, it is unnecessary to parallel two or more exciters controlled by the same regulator. This makes this regulator particularly adapted to the automatic regulation of alternators having exciters with different voltage characteristics, one regulator being capable of controlling the voltage of a number of alternators in parallel. The number of relay contacts required for the exciter depends, to a great extent, on the characteristics of the exciter. The number of machines that can be controlled by one instrument, when the

regulator operates directly on the exciter field rheostats, is consequently only limited by the possibility of fitting a sufficient number of relay contacts on the instrument.

If the exciter field currents are large or the number of relays required for all the machines to be regulated is more than can be accommodated on one regulator, this instrument can be made to operate on the field rheostat of a small shunt-wound machine whose armature is connected across the exciter fields to be regulated (fig. 9).

The operation of this scheme is briefly as follows: At light loads, the excitation of the small auxiliary generator F is automatically weakened by the regulator, so that it tends to run as a motor taking power from and thus weakening the exciter field. As the load increases, the excitation of the auxiliary is automatically increased until a point is reached at which no current passes through its armature. If the excitation be still further increased, the auxiliary machine becomes a generator, and assists the exciter field D. The regulator in this case need only have one or two pairs of contacts, giving the advantage of simplicity in the regulator itself.

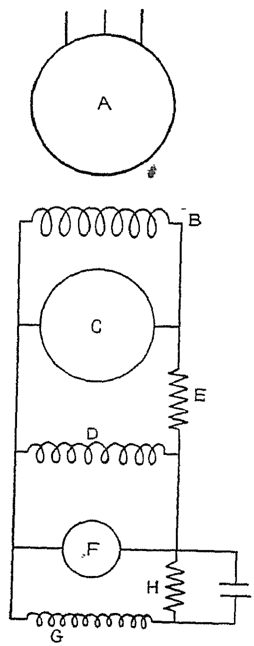


Fig. 9

If the exciters have different characteristics, a resistance is permanently connected in the fields of all those having a high voltage, so that the effective pressure of all machines is reduced to the voltage of the lowest pressure exciter.

The other most widely used regulator, falling within the class of instruments which short-circuit a portion of the field resistance, is that known as the Tirrill (fig. 10). In general it is not dissimilar to the Metropolitan-Vickers regulator, except that in the Tirrill regulator the exciter coil is the device used to overcome the hunting of the simple regulator. See diagram, fig. 11.

There is a main control coil (1) connected across the mains, the pressure of which is to be regulated, as in the regulator previously described. The plunger is connected to a lever (2) which is counter-balanced by a weight. This coil is so designed and adjusted that for a constant voltage the pull on the core is independent of the position of the core in the winding. Thus, if a constant voltage be applied to a coil, the lever will remain balanced in any position in which it is placed. The exciter control magnet (3) is connected direct across the exciter, the core being linked to the lever (4). It will be appreciated that the pull on the core varies as the square of the current in the coil, while the pull of a spring varies directly with the elongation. In order to get proper balance on the lever (4), recourse is had to a multiple system of springs which are adjusted to come into action one after the other. This gives a result approximating to the one required, but even with this the

exciter voltage range between full and no load must be kept within fairly close limits.

With a decrease in the exciter voltage, the lever (4) tends to rotate in a clockwise direction. The main control coil lever (2) and the exciter control lever (4) are each fitted with one contact, which contacts co-engage at (5). When there is a decrease in voltage across their respective coils, these contacts will tend to come together, and with an increase in voltage tend to separate. The relay coils (6) are wound equally but differentially. One of the windings is connected permanently across the exciter and the other through the main control contacts (5). When contacts (5) make circuit, the fluxes due to the relay windings are neutralized, removing the magnetic pull on the relay

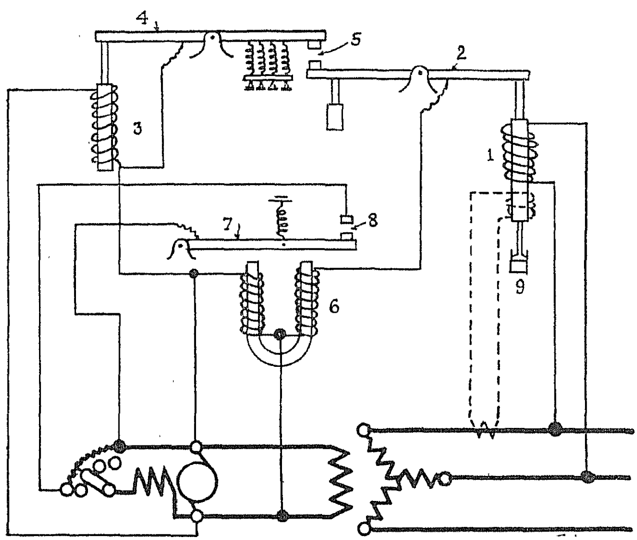


Fig. 11.—Simplified Diagram—Tirrill Regulator

armature (7), so that the spring which is attached to the armature at once pulls up the lever and closes the relay contacts (8). These contacts are connected across the exciter field rheostat.

The cycle of operations is as follows: Assuming that the pressure begins to fall, the lever (2) will start to rotate in a clockwise direction until the contacts (5) close. Both relay coils (6) are thus energized and cause the contacts (8) instantly to close as previously described, thus short-circuiting the exciter field rheostat. The exciter voltage will then rise until the alternator field is so strong as to raise the alternator voltage sufficiently to restore equilibrium in the main control magnet lever (2). The exciter voltage continues to increase by a small amount and moves the lever (4) until the contacts (5) part. Up to the instant of establishing equilibrium on the lever (2), both contacts were moving together in an upward direction. Directly the contacts (5) part, the relay contacts (8) part also, and thereby insert the resistance of the exciter rheostat in series with the exciter field. Since the

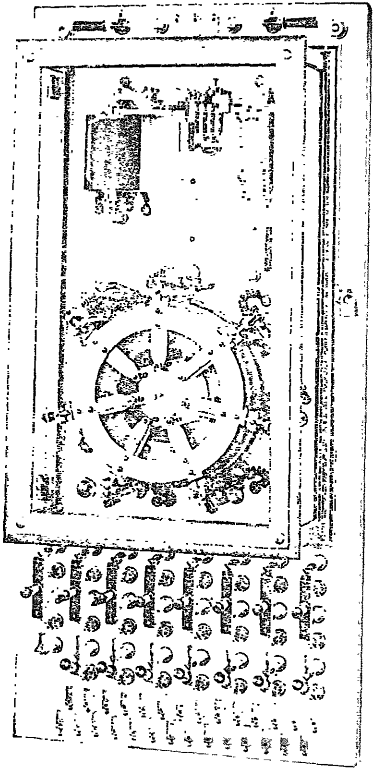


Fig. 10.—Tirrill Voltage Regulator

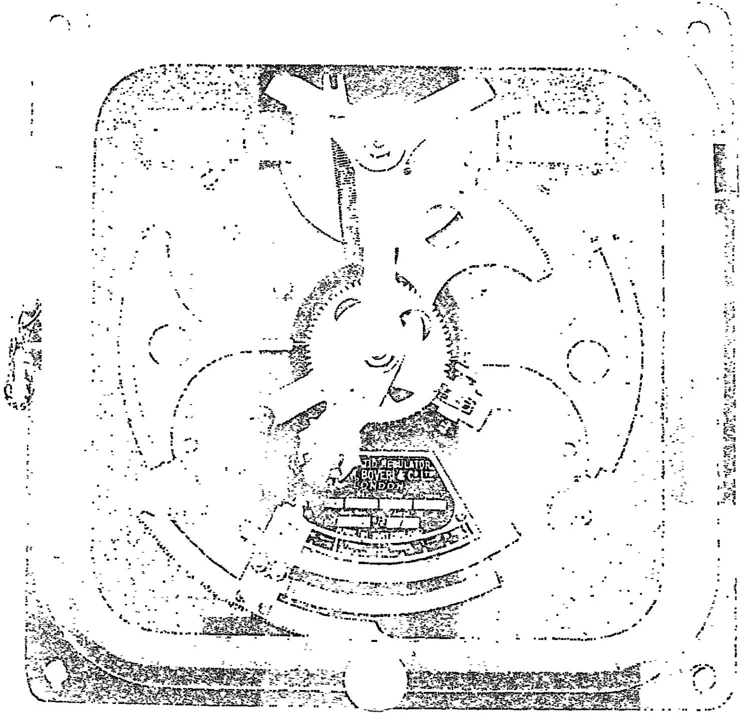


Fig. 12.—Brown-Boveri Voltage Regulator

movement of the core of the main control magnet (1) is controlled by a dashpot (9) it is not so free to move as the exciter magnet lever (4), and therefore the lower contact can be considered stationary as long as the supply voltage is constant. Assuming that this condition holds good for a time, the action of the regulator is to maintain the average exciter voltage at the figure necessary to keep the alternator voltage constant, i.e. to maintain the main control lever (2) in equilibrium. The subsidiary cycle is then as follows. The exciter voltage tends to fall rapidly, due to the relay contacts having inserted the exciter field rheostat in the field circuit. The exciter volts fall sufficiently to re-engage the main contacts (5), the main control coil lever (2) not moving in the short time required for the exciter control coil lever (4) to re-engage the contacts. The closing of these contacts again releases the relay armature (7) and the relay contacts (8) come together, short-circuiting the exciter rheostat. This causes the exciter voltage to increase again sufficiently to move the lever (4), and thus open the main contacts. This cycle of operations repeats itself, giving what is in effect a vibratory motion to the lever (4). The frequency of the vibration is dependent on the sensitiveness of the exciter control magnet (3), and the rate at which the exciter field builds up and demagnetizes. This condition is maintained until a change takes place in the alternator supply voltage.

If the load decreases, the alternator voltage commences to rise, and the preceding cycle of operations takes place in the reverse manner, the main contacts opening, &c. The main control lever (2) then moves in a counter-clockwise direction, parting the contacts (5), and consequently causing to open the relay contacts (8), thus reducing the exciter voltage. The main control lever (2) continues this movement until equilibrium is again established, after which the exciter voltage continues to fall by a small amount, closing the main contacts (5) and restarting the vibratory action referred to above.

The diagram shown indicates one relay and exciter only. The number of relay contacts required depends on the characteristics of the exciters and the number that may be required to run in parallel. When a number of machines are to be controlled by one regulator, it may be necessary to parallel the exciters and to insert a small resistance in the main field circuits for equalizing purposes.

The relay contacts (8) are protected by a condenser of suitable capacity, connected across them. Reversing switches are also employed to change the direction of the current through the contacts and thus equalize the wear. For use with this regulator the portion of the exciter field rheostat which is short-circuited must be sufficiently large to give a voltage range from about 65 per cent to 120 per cent normal voltage, were this resistance permanently connected. In practice, of course, the resistance is cut in and out of circuit so rapidly that these variations are never actually reached.

The Brown-Boveri regulator is a combination of the control magnet and the rheostat itself, and thus falls into group 2. It consists in the main of an electro-magnet, which is connected across the terminals of the alternator

whose voltage is to be controlled. This magnet acts upon a cylindrical aluminium armature, whose motion is retarded by a system of springs.

The movement of this armature is transmitted to contact sectors which *roll* over the fixed contacts of the variable resistance. This rolling action is a distinguishing feature of this regulator, as for a relatively small movement of the armature the contact sectors roll with very little friction over a large number of contacts, and so insert or cut out a considerable amount of resistance in the field circuit of the exciter.

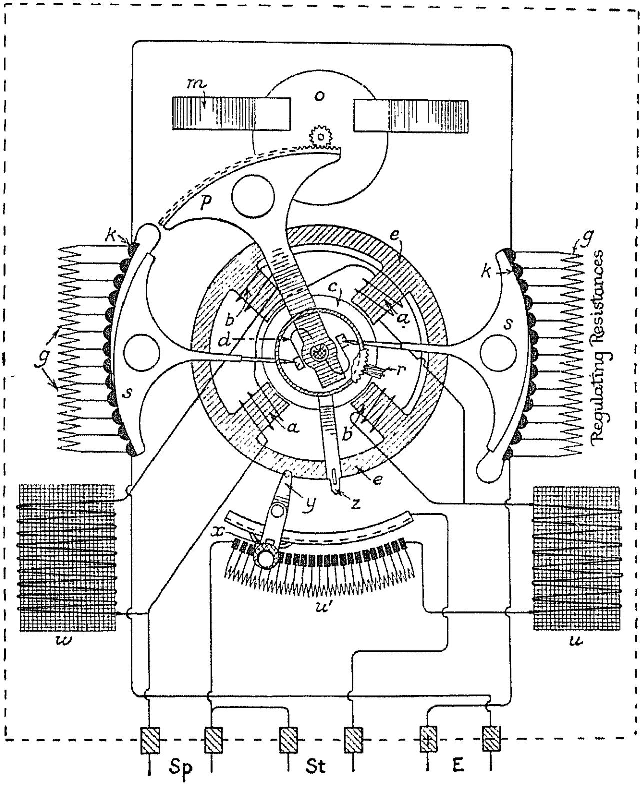


Fig. 13.—Diagram of Internal Connections of Brown-Boveri Regulator

Referring to fig. 13 it will be noticed that a light cylindrical armature *c* is pivoted between the poles of the electro-magnet *e* which forms part of the driving system. The poles are wound alternately with coils *a* and *b*, the currents in which are relatively displaced in phase, this being brought about by the resistance coil *w* in series with the coils *b b*. A rotating magnetic field is thus produced which, acting on the armature *c*, causes it to exert a torque which is dependent upon the pressure of the circuit. The torque of this electro-magnet is opposed and balanced by the constant mechanical torque of a spring system, comprising a flat spiral main spring and a small supplementary spring. The latter compensates for the variation in tension

of the main spring. In this way the resultant torque opposing the armature is made constant for all positions of the armature.

The armature and all moving parts are made as light as possible to eliminate friction and inertia. The armature *c* is made of aluminium and is pivoted between jewelled bearings. The contact sectors *s* also are centred in jewelled bearings mounted on the springs *d* which are carried by the armature spindle, and which hold the sectors against the contacts *k*.

It will be seen from fig. 13 that the movement of the armature *c* will cause the contact sectors *s* to roll over the contacts *k*, due to the point of support of these sectors being displaced from the centre of rotation of the armature *c*. To prevent hunting, a damping device is fitted, comprising an aluminium disc *o* which rotates between the poles of two permanent magnets *m*. The movements of the armature are transmitted to the disc by means of a toothed quadrant *p*, and a small pinion. This quadrant is connected flexibly by a sleeve on the armature spindle to the end of a flat spiral spring, the other end of which is fixed to the armature itself. This spring is in the normal condition so long as the moving parts are in equilibrium, but as soon as an alteration in the potential takes place and the armature moves in one direction or the other, the spring is either extended or compressed. It will be seen, therefore, that there is a small time-lag between the movements of the armature and damping quadrant which allows the armature to carry the contact sectors momentarily ahead of the required new position at the moment the pressure changes, after which it adjusts itself to the correct position. This flexibility between the damping device and the sectors varying the field resistance value is devised to overcome the effect of the self-induction of the field winding.

In order to render the regulator independent of variations of temperature and frequency, the resistances *u′* and *u* are provided in series with the windings *a a b b* on the electro-magnet. The resistance *u′* is variable, and when a current transformer is connected to the terminals S*t*, by altering the position of the movable contact *x*, the pressure can be made to increase with load.

This type of regulator can only be made to operate on one exciter circuit at a time. When two or more generators are operating in parallel, special arrangements are necessary. If the station be comparatively small it is feasible to regulate on the largest machine running and allow the smaller sets to trail. With larger generating sets it is customary to have a separate voltage regulator for each machine. In this case a series transformer is inserted in the main conductor of each generator, the secondary being connected to terminals S*t* on fig. 13. By adjusting resistance *u′* each regulator can be given a compounding effect so as to ensure every generator taking its fair share of the lagging current.

The three regulators described have been selected as typical of their classes, and as being widely used. The Taylor-Scotson regulator in this country, the Fuss regulator on the Continent, and the Westinghouse-Tirrill regulator in America are all successful examples of instruments falling into group 1.

There are fewer devices in group 2, the Thury regulator being the only one besides the Brown-Boveri to be at all freely employed.

When a number of machines are operating in parallel with a separate automatic voltage regulator on each machine, a special compensating device is necessary to prevent cross-currents between the various generators. This load-sharing arrangement consists of a compounding coil on the main control solenoid, the coil being excited from a series transformer in the circuit of each generator.

With the potential coil across phases A and B the series transformer is in phase C, the current coil being so connected that, with a lagging current on the alternator, it tends to assist the voltage coil. It thus follows that the excitation is reduced on those generators the current from which lags the most, while correspondingly the excitation is increased on those machines which supply current with the greatest lead. The effect is consequently to control all machines so as to operate at the same power factor and share the load equally.

In a hydraulic station, speed of operation is of first importance, since it is essential that the voltage should not become excessive, should the governor fail to control the turbine on a reduction in load. Reference is made under "Protective Systems" to the various means adopted to take care of this emergency condition. With a well-designed automatic voltage regulator no additional device, such as over-voltage relay, is needed, unless there is a possibility of the voltage regulator being removed from service at any time.

3. Oil Switches and Circuit-breakers.—Strictly speaking, the term "oil switch" should only be applied to a non-automatic device, which is not usually called upon to open an excessive current. A similar automatic device should be termed an oil circuit-breaker, following the long-standing practice with air-break apparatus. The term automatic oil switch, although well understood, is now being dropped.

As a device for rupturing high-potential A.C. circuits the oil switch has now been in use for some twenty years or more. Although several manufacturers have produced designs which are capable of giving satisfactory service within fairly closely understood limits, there is not yet any clearly defined method of design, except in regard to insulation and normal current-carrying capacity. The design of oil switches and circuit-breakers from the point of view of current rupturing capacity is still, to some extent, an art based on experience, rather than a precise science.*

Researches to determine the scientific bases for oil switch design have been carried out in the past, and are still in progress. In Switzerland Dr. Bruno Bauer has presented to the Schweizerische Elektrotechnischer Verein (Swiss Association of Electrical Engineers) a series of reports detailing his

* Empirical formulæ have been devised to fix dimensions for switches of certain general types, and the breaking capacity ratings determined in this way are closely borne out in tests with large-capacity plants.

mathematical considerations, and certain tests which he made on small switches breaking powers of one or two thousand k.v.a.

In this country a strong committee has been formed by the British Electrical and Allied Industries Research Association. Having first collated all available data on researches, they have now commenced to carry out a large programme of original research work.

Much has been done, also, by the larger manufacturing concerns, such as the Westinghouse and General Electric Companies in America, the associated British firms, the Metropolitan-Vickers Electrical Co., and the British Thomson-Houston Co., and on the Continent by Brown, Boveri, and the Allegemeine Electricitäts Gesselschaft. Such work has naturally aimed to improve the designs adopted by the firms concerned and is not publicly available.

There is, however, general agreement that the following factors are the principal ones affecting the satisfactory design of an oil switch, all except the first two having a bearing on the question of ultimate breaking capacity.

1. Insulation.
2. Normal current-carrying capacity.
3. Speed of opening.
4. Location and number of arcing contacts.
5. Length of break.
6. Head of oil.
7. Volume of oil.
8. Quality and viscosity of oil.
9. Clearances under oil and in air.
10. Volume of air in chamber above oil.
11. Strength of oil tank and top chamber.

In all oil switches the end in view is to interrupt the circuit in the shortest possible time after the contacts commence to separate. When this type of apparatus was first introduced it was believed that the arc was finally extinguished when the current wave first passed through the zero point.

With the comparatively small currents and pressures which were then handled this claim was possibly true, but oscillograph records taken under modern conditions frequently show that the arc has persisted for some cycles after the contacts have parted. In certain cases it is seen that the arc has been extinguished as the voltage reached a zero point, but that it was re-established when next the voltage wave approached a peak value.

When an oil switch operates, an arc is formed between the contacts, and the heat breaks up a certain amount of the oil immediately adjacent, the gases thus formed rising to the surface in the form of a bubble. The gas bubble is formed of a mixture of about 60 to 70 per cent hydrogen, 30 to 40 per cent methane and ethylene, with small quantities of oxygen, nitrogen, and carbon-dioxide. If a " chimney " be formed, oil vapour and free carbon may also be present. Within wide proportions a mixture of these gases with air is explosive. If the switch be operating beyond its capacity the bubble may be

of such size as to form a continuous gas path or " chimney " from the contacts to the oil surface, when the arc will fire any explosive mixture which may be present, possibly bursting the switch top.*

All switch " explosions " are not caused in this way, but more frequently are really the mechanical failure of the tank or some other part under the momentary pressure due to the formation of a large bubble of gas, which, however, is not ignited.

In either case the volume of gas liberated is the key to the situation, as by reducing this the instantaneous pressure is reduced and also the formation of a gas chimney is avoided.

The volume of gas liberated from a given oil is proportional to the current, and to the time during which the arc persists. A study of the generator die-away curves shown in fig. 26, p. 176, makes it clear that by delaying the opening of a switch the current can be reduced, and it is now clear that once the contacts start to open, they must complete their travel as quickly as possible.

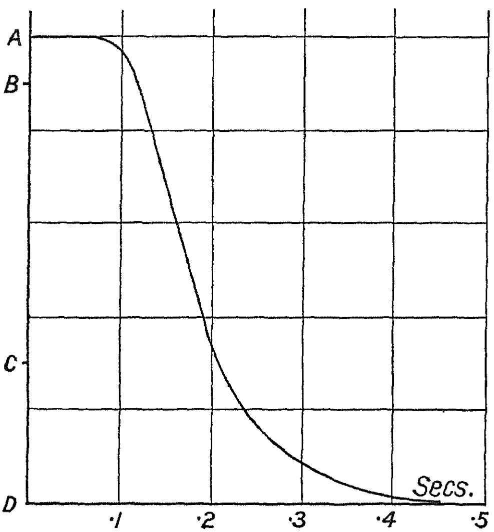


Fig. 14.—Typical Time-travel Curve for Oil Switch

In fig. 14 is shown the time-travel curve of a typical oil switch. In this switch auxiliary contacts are provided to take the arc, these being carried on springs in such a way that during the time interval AB the main brush contact is moving downwards, while the auxiliary arcing contacts remain in place. When the moving element has accelerated to some extent, the arcing contacts part, and from B to C the travel is quite unrestricted, this being the period during which the arc is broken. In the final portion of the stroke, between C and D, a dashpot comes into action, to absorb the shock in bringing the moving parts to rest.

As a result of his investigations made with very small oil switches, Dr. Bauer expressed the opinion that the most desirable speeds for the moving contacts at the instant of parting are between 60 and 120 cm. per second (*S. E. V.*, August, 1915). Above and below these figures he found that the arcing time for a given current was prolonged.

* Since some air space must necessarily be left above the oil level to prevent splashing and to provide an expansion chamber for the arc gases, the natural idea is to make it of such volume that an explosive mixture cannot be formed. This is not practicable, however, and [illegible] is d for d aling with the problem.

The practical experience of many makers, in switches of the largest size, has disproved this theory. Switches made by British and American firms operate at between 100 and 700 cm. per second. It has been conclusively shown in certain cases that an increase of switch speed from 120 cm. per second to 400 cm. per second has resulted in an increased breaking capacity. In the majority of cases these high speeds are obtained by means of accelerating springs which assist the action of gravity and the natural spring of the contact element itself.

The speed to which reference is made is measured when no current is passing. In switches where the terminal studs and bridge piece form a loop (the vast majority of cases) there is a considerable electromagnetic effect tending to repel the moving contacts. As this varies with the current, the no-load condition is always taken as a basis for comparison.

In those forms of switch in which the contact-carrying rods pass through the switch top, the gas formed at the instant of opening may exert sufficient pressure on the piston thus formed to slow up appreciably the opening movement. In such designs it is essential to reduce the diameter of the suspension rods as far as possible. The mechanism is usually so arranged that as small a weight as possible must be moved in opening, and that the accelerating period is as short as possible.

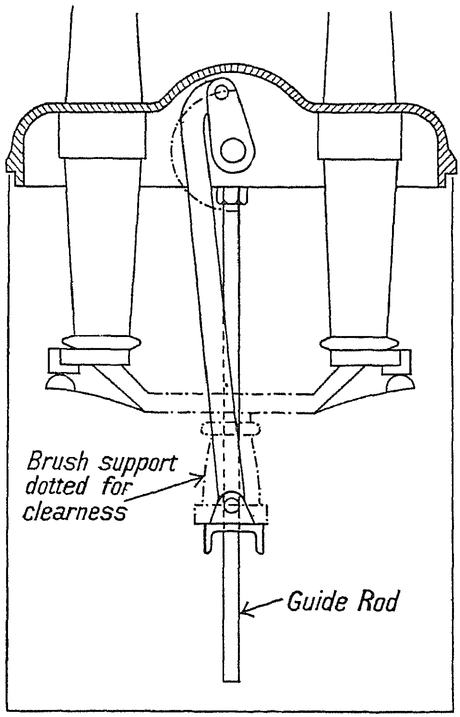


Fig. 15.—Construction of Continental Hand-wheel Operated Switch

In the majority of Continental-built switches the operating shaft turns through approximately 180°, the switch contacts being carried at the end of a connecting rod, in the manner indicated in fig. 15. In such a case quick acceleration in the downward movement is difficult to secure, and with these switches speeds of 50 to 100 cm. per second are more usual.

Considerable variation exists in the design of oil-switch contacts, both in regard to the contact surfaces themselves and also in their disposition within the tank. It has been demonstrated that copper is the best material, both for current carrying and for arcing contacts. The more widely used forms may be grouped as follows:

1. Controller finger.
2. Laminated brush.
3. Butt.

The controller finger type of contact is generally arranged as indicated in fig. 16, with pairs of spring-mounted contacts, between which moves a wedge-shaped bridging piece. Such contacts are simple to construct and to adjust, since they are practically self-aligning. Accurate setting of the moving wedge is of no great importance, since the pressure of the contact fingers is approximately the same within a wide range of wedge position. The contact pressure is usually of the order of 8 lb. per square inch, with a contact current density of 100 to 150 amp. per square inch. Several fingers in parallel are used for heavy currents.

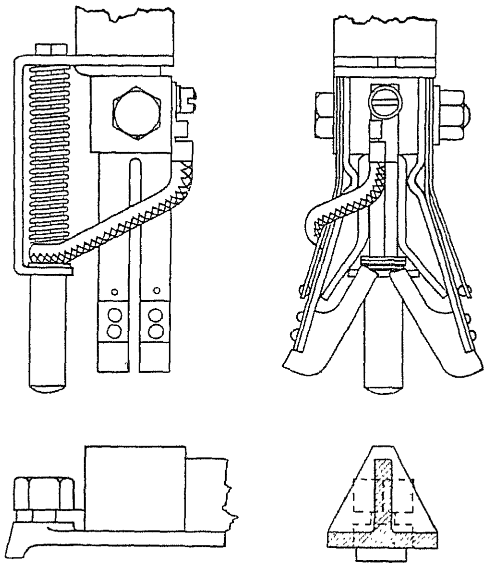


Fig. 16.—Controller Finger Main Contacts, with Butt Arcing Contact

Although on certain cheap switches the arc is broken on the main wedge contacts, this is not desirable, since burning of the contact faces must result. The better way is to fit separate arcing contacts which are longer than the rest, and which bear on another part of the bridge piece. These are not relied on to carry current, save at the instant the contacts part. The main objection to this form of contact is that a considerable amount of the total travel is lost, in order to ensure the main fingers being safely clear of their contact faces before the arc is formed. The total space occupied is also a serious item on heavy current switches.

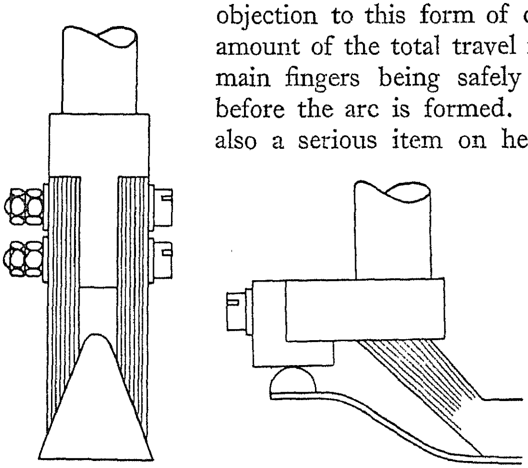


Fig. 17.—Typical Brush Contacts

The brush form of contact is never used by itself, since it is totally unsuited to opening an arc, although an excellent means of carrying current. In the usual construction the leaves of the brush meet the contact face at an acute angle, in the manner shown in fig. 17. The left-hand form is that adopted by Carl Maier, in Switzerland, while the right-hand construction is used by many makers both in Great Britain and abroad. Brushes such as the latter are generally worked at a current density of 250 amp. per square inch,

the contact pressure varying between 15 and 50 lb. per square inch. Much more accurate workmanship and setting is demanded than for the controller finger type, and a very small variation in the relative positions of contact block and brush holder will seriously affect the conductivity. The reason for this is easily seen from the illustration, fig. 18.

A third form of brush contact which presents some advantages over those

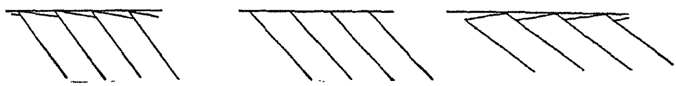


Fig. 18.—Effect of Varying Pressure on Inclined Brush

previously described is that known as the "wound" brush, on account of the method of its manufacture (fig. 19). In this the brush leaves bed practically normal to the face of the contact. Comparatively wide variations in the relative positions of brush holder and contact block do not appreciably affect the contact of individual leaves, as the flexure takes place at the back of the curve.

A series of comparative tests on brushes shown in the last two illustrations was made to determine the effect of varying contact pressures, the curves obtained being given in fig. 20. It will be observed that with the wound brush the brush-holder setting and hence the contact pressure can vary within a very wide range, while retaining a reasonable contact drop.

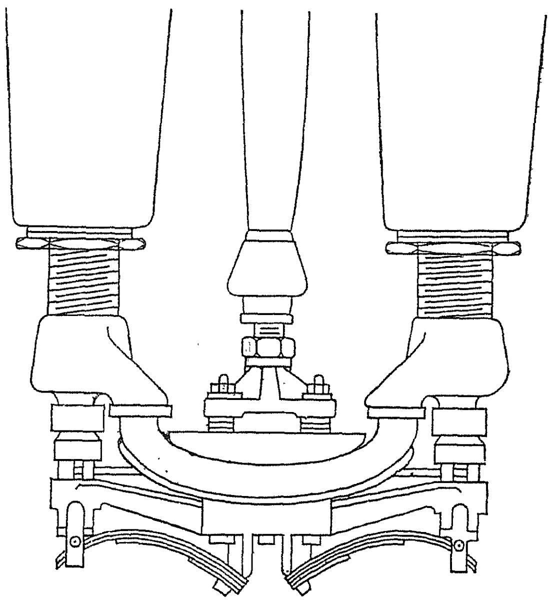


Fig. 19.—"Wound" Brush with Butt Arcing Contacts

The wound brush is usually worked at a current density of 500 amp. per square inch, with a contact pressure of 100 lb. or more per square inch. It will be noted that the value "lb. per ampere" is practically the same in the two forms of brush. As the wound brush can safely be worked at twice the current density and consequently weighs less and exposes a smaller surface to the oil, it possesses considerable advantages when large currents have to be handled.

In some large plants, where the short-circuit currents have amounted to perhaps 40,000 amp. or even more, trouble has been experienced due to the brush leaves being deflected. The magnetic field produced by so large

a current passing round the loop formed by the switch studs has produced a force sufficient to open the circuit momentarily, and thus has burned the main contacts. To avoid this the reversed wound brush has been applied. With this it will be clear that the effect of the magnetic field will be to press the brush into tighter contact.

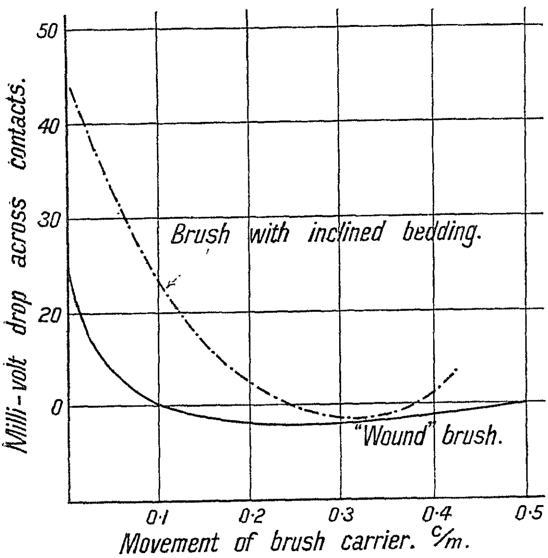


Fig. 20.—Effect of Varying Brush Setting

As already stated, brush contacts must always be furnished with supplementary means for taking the final arc. This is frequently in the form of a solid block of copper carried on a flat spring, which is riveted to the main brush in the manner shown in fig. 17.

A better method is to use the butt contact, shown with the wound brush in fig. 19. In this the arcing blocks are so mounted that they travel in a truly vertical path, parting contact after the main brush is well clear. The peculiarity of this construction is that the contact improves with wear, apparently due to the arc pitting one face and leaving a corresponding globule of copper on the opposite contact face.

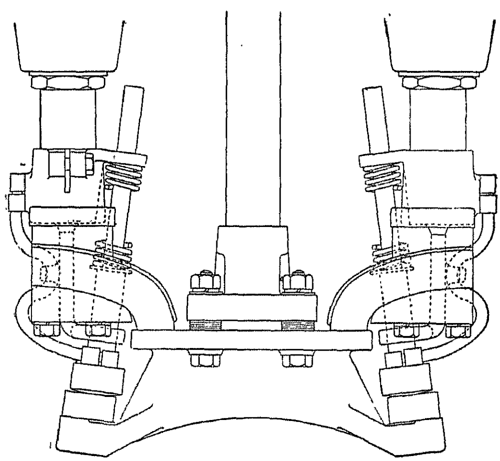


Fig. 21.—Reversed Brush, with Butt Arcing Contacts

No matter what type of contact is employed, the greatest care in design is necessary to obtain low contact resistance on the arcing surfaces. Where the ratio between the resistances of main and auxiliary contacts is high, the current does not transfer cleanly from one to the other when opening circuit, and burning of the main contact surfaces results. Butt contacts alone are frequently used for handling small currents. They become unpractical for large currents owing to the low current density at which they can be worked.

In high-voltage oil switches special care must be taken to avoid corners or edges on the contacts, at which brush discharges might form. In fig. 22 is shown a shrouded quick-break contact used by the Westinghouse Co. All moving parts are entirely enclosed within metal bells which have perfectly rounded contours.

A considerable difference of opinion exists in regard to the location of

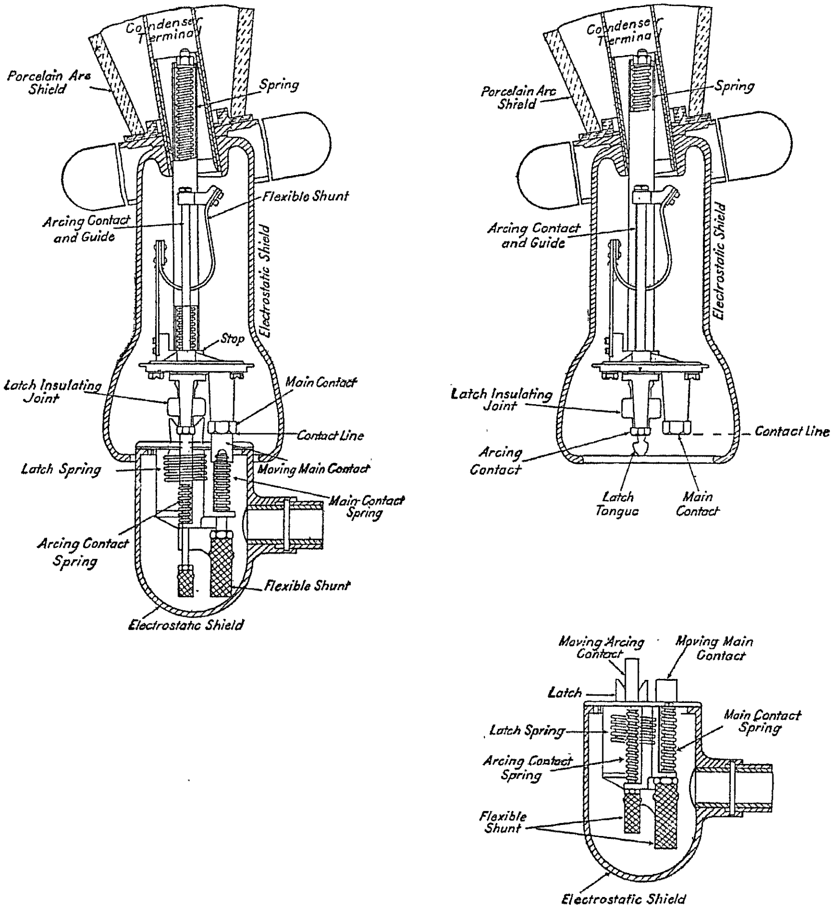


Fig. 22.—Contacts for 135-K.V. Switch

arcing contacts, and also as to whether a single, double, or multiple break is best.

The double-break switch is the earliest and the most widely used form, and single and multiple breaks may be regarded as attempts to improve upon it. In the majority of designs the two contacts are within the same oil tank, and are so arranged that full advantage is obtained of the mutual repulsion between the arcs. The notable exception to this arrangement is the " pot " switch built by the General Electric Co. of America. Here each

break takes place in a separate oil chamber, and no electro-magnetic effect is available to assist in rupturing the arc.

The single break, as advocated by Mr. R. W. Gregory, is embodied in the largest oil switch equipment built by Messrs. Reyrolle. It will be noted that in this switch the arcing contact is located above the main brush and that there is an entirely free and unrestricted path up to the surface of the oil. By causing both elements of the arcing contacts to move (instead of having one stationary contact as is usual) a very high speed of final break is obtained.

The multiple break finds most adherents among Continental builders, where switches with six and even ten breaks per pole are to be found. In the beginning no doubt the increased number of breaks was adopted to get a sufficient final break for very high voltage work, while retaining the rotary mechanism which was used for lower voltage switches, and which could not well be arranged to give a longer travel. With a given speed of the moving contacts, however, the speed at which the arc is drawn out is increased in proportion to the number of breaks. It has not yet been conclusively shown that the arcing time is reduced in direct proportion, but published tests indicate a great improvement in this direction.

In the early days of oil switch design it was frequently assumed that the breaking capacity of an oil circuit-breaker was a direct function of the length of break. This has been shown to be incorrect. With switches of different design, but of similar known rupturing capacity, the length of break may range from 20 in. down to 6 in. It now appears that for a given form of switch the length of break should vary rather with the voltage, and be such that a considerable margin is obtained over the maximum length of arc which can be drawn at whatever speed of operation be adopted.

The head of oil above the arcing contacts and the volume of oil adjacent to the contacts are related to the volume of gas which may be liberated safely by the arc. In most oil switches the necessity for avoiding "chimney effects" alone dictates the head of oil. On apparatus for very high voltage, however, creepage over the insulator surface under oil may become the predominant factor. Considerable differences exist between Continental practice and that followed in this country and in America in the distance from the arcing contacts to the tank through the oil. On the Continent tank linings are unusual, as are also phase barriers under oil in three-pole switches. It follows that much greater clearances must be allowed to avoid the incandescent gas bubbles from the arc either reaching the earthed tank or to the adjacent phases. By using insulating tank linings and phase barriers the overall dimensions of apparatus are greatly reduced. Apart from cooling, there seems little advantage in having a big volume of oil between the contacts, as no gas can be formed in, or even reach to such a position. No earthed metal should be below oil-level in any position where the gas bubble might be expected.

As regards the oil itself, a mineral oil only should be employed. Ordinary

transformer oil is frequently used for switches operating at usual temperatures. Where the switches are operating out of doors in a very cold climate, an oil with specially low freezing-point must be used, to prevent the switch being held in by frozen oil. A typical specification for switch oil which thickens at 10° C. is as follows:

"The oil shall be a pure mineral oil, free from moisture, acid, alkali, or sulphur compounds.

"The breakdown voltage when measured between spheres $\frac{1}{2}$ in. diameter, separated 0·15 in., shall not be less than 22,000 volts.

"Viscosity at 40° C. measured by Redwood viscometer, 100 seconds.

"Flash-point, 171° C.

"Fire-point, 198° C.

"Specific gravity, 0·86."

A special grade of oil which does not thicken until 45° C. has a rather higher breakdown voltage, flash-point 126° C., fire-point 149° C., and specific gravity 0·83.

In regard to the breakdown voltage, the slightest trace of moisture in the oil will reduce considerably the puncture value. The presence of carbon particles in suspension has a similar effect, and this is bound to be the case in any switch which has opened a few times on load, especially if no time has elapsed to allow of the carbon settling to the bottom. Very liberal clearances must, therefore, be allowed between live metal and earth under oil.

The precise determination of the pressure which may be developed in a switch tank has not yet been attained. In his report Dr. Bauer stated he had found approximately 46·5 c. cm. of gas, at 25° C. and atmospheric pressure, were liberated per kw.-second arc energy. This figure has been confirmed by other investigators. The determination of arc energy, however, requires a definite knowledge of the arc resistance or voltage.

Dr. Bauer's figures may alternatively be put in terms of the arc amperes, the system voltage, and the arcing time. Thus he gives 3·25 c. cm. of gas at 25° C. and atmospheric pressure liberated per k.v.a. per second. This amounts to assuming a constant relation between the system voltage and the arc voltage. Experience with numerous short-circuit tests shows this assumption to be incorrect.

In actual tests on large circuit-breakers tank pressures of 200 and even 300 lb. per square inch have been recorded.

It is important that provision be made to ventilate the air chamber above the oil, so as to prevent retention of a possibly explosive mixture. Such vents should take the gases well clear of the switch terminals, as if the hot, ionized gases are permitted to escape between live metal parts in air, the spark-over voltage will be very greatly reduced. To this cause have been traced many cases where breakdown has occurred between terminals with apparently more than ample spacing.

British switchgear makers have generally agreed that the following minimum clearances between opposite phases are required.

Rated Pressure.		Minimum Clearance in Air.
3,300 volts.	....	2 in.
6,600 ,,	....	$3\frac{1}{2}$,,
11,000 ,,	....	5 ,,
22,000 ,,	....	$9\frac{1}{2}$,,
33,000 ,,	....	14 ,,

Such specified clearances are in most cases somewhat higher than those required by the V. D. E. rules, and are more than double the arc-over distances between needle points in air, found in the laboratory to correspond with the specified test voltages.

For all switches the B. E. S. A. specification calls for a test pressure of 2000 volts, plus $2\frac{1}{4}$ times the normal voltage, this being, of course, the r.m.s. value. The same test voltages are imposed by the Standardization Rules of the American Institute of Electrical Engineers.

In the section dealing with added reactance an arrangement was described by which the reactance is normally short-circuited and only comes into action when an oil circuit-breaker has to operate automatically. As a rule two separate circuit-breakers are employed for this purpose, the reactance being mounted externally. At one stage of development all three elements were confined within a common structure which was known as a reactance circuit-breaker. The two switch movements were contained within one tank, the mechanism being arranged so that when the short-circuiting element had travelled half its stroke, it actuated the trip of the switch taking the final break.

The idea was to divide equally between the two switch elements the work of interrupting the load, but this was not always possible. Objection was raised to the use of this device on the grounds that by switching current suddenly into a coil built in so small a space, voltage surges might be expected of sufficient magnitude to threaten the insulation. The mechanism was quite complicated, and it was quickly found possible to build oil circuit-breakers of conventional design having breaking capacities as large as could be handled with the reactance circuit-breakers.

A similar arrangement, using resistance in place of reactance, is very widely used on the Continent. The majority of oil circuit-breakers installed in big Continental power stations to-day are of this type. The primary object with the reactance circuit-breaker was to limit the arc-rupturing duty on the circuit-breaker itself, and not to improve conditions in other parts of the system, which get the full shock due to the initial short-circuit current rush. In Continental practice switching resistances are used to perform the following functions:

1. To limit the magnetizing current rush when switching in transformers and induction motors.
2. To limit the voltage surge when switching out a transformer.

3. To limit the voltage surge when switching long transmission lines.
4. To limit the duty on the oil circuit-breaker when operating automatically.

The value of resistance required for purpose 1 is different from that desirable for purpose 2. As it is clearly impracticable to provide two sets of switches and resistances, to be used when closing and opening circuit respectively, a compromise value of resistance is always selected. Engineers in this country and in America are almost unanimously of opinion that the advantages gained are not worth the extra complication, and there are only two or three large users of transformers in Great Britain who use switching resistances in this way.

The limitation of voltage surges on a transmission line was of greater importance until the recent improvements in lightning arresters were evolved. A modern arrester is capable of discharging any over-tension due to switching operations which is of sufficient magnitude to be harmful to the line or connected apparatus. This use of the impulse spark gap has not yet extended to the Continent, however, so that there the use of resistance circuit-breakers can frequently be justified.

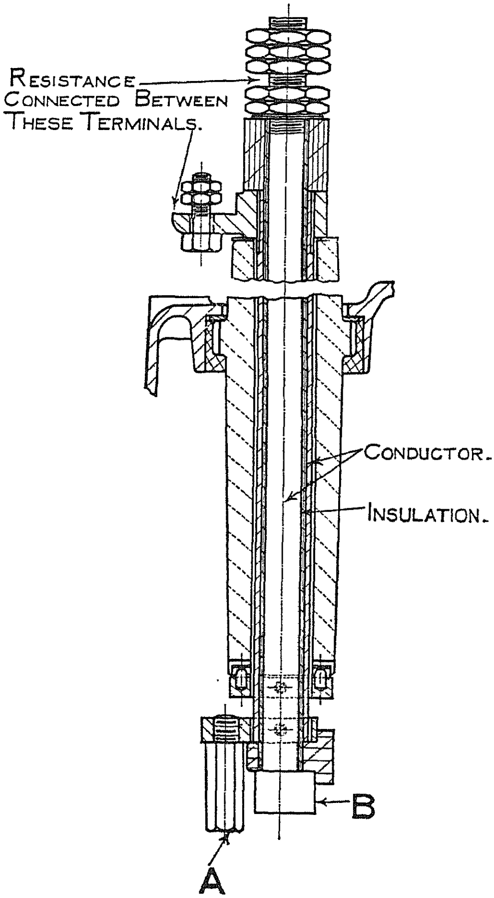


Fig. 23.—Concentric Switch-stud

When using resistances for any of these purposes, it is usually considered sufficient to connect the resistance between the main and a leading contact, since the bulk of the arc when opening should take place on the one contact. In fig. 23 is illustrated such an arrangement. The resistance is connected between A and B, which are lightly insulated from each other. When closing, the moving arm first meets contact A, thus putting the resistance in the series circuit, while at the completion of the stroke, contact is made with B, and the resistance is cut out of circuit. The time for the movement from A to B is very short, being of the order of 0·05 sec., and the resistance need only be of very small

dimensions. It is sometimes carried in the oil tank beneath the moving element, to which it is connected by flexible leads.

There has been much discussion regarding the design and the use of switch protective resistances, which, on a big system, may attain considerable size. In this case the resistance and main contacts should be well separated and the resistance so proportioned that the maximum short-circuit current at the point of installation is reduced to half when the resistance is in series. Each of the two sets of contacts will then have equal arc-breaking duty in the worst case. When the fault is at some distance from the switch, or when it is not a dead short-circuit, the work will not be equally divided between the two contacts, but will be more severe on the final break. For this reason switch protective resistances are usually given an ohmic value somewhat in excess of the total circuit impedance from generators to switch. Despite the very short time during which the resistance is in circuit, it is frequently necessary to use cast-iron grids on large-capacity low-voltage systems. These are bulky and awkward to accommodate in switch structures, while the circuit-breaker itself is complicated by the necessity for extra contacts. In the end it is generally better to build a simple oil circuit-breaker of sufficient dimensions to enable it to interrupt the circuit without need for external resistances. Moreover, it is a doubtful question whether such resistances do reduce the total heat which must be absorbed by the switch oil.

4. Selection of Oil Circuit-breakers.—An oil circuit-breaker serves two distinct functions; to carry continuously and without undue heating a definite current, and, in emergency, to interrupt a current which may be many times greater than the normal load. Of the two, the latter is the more important, since the safety of all connected apparatus depends upon the successful automatic operation of the circuit-breaker. The power which can be dealt with under this head is termed the breaking capacity, or the ultimate rupturing capacity of the device.

There is some divergence in the manner in which breaking capacity is stated. At one time it was common to see a circuit-breaker rated as suited for use with a generating plant of stated k.v.a. capacity. This is clearly wrong, since the manner of connection can entirely alter the duties of a circuit-breaker, and great differences exist in the performances of generators under short-circuit conditions.

The modern methods are to give either the maximum arc current or the maximum k.v.a. which the circuit-breaker can actually interrupt, the latter figure being the product of the maximum arc current, the normal line voltage, and the factor corresponding to the number of phases. The former method is the American standard and the latter British, although it is permissible to use either in this country.

Neither method is perfect, since the limit current for a given circuit-breaker varies with the system voltage, while on the other hand a short-circuit close up to the generating plant will bring down the system pressure below normal line voltage. Provided the limitations of these definitions are borne in mind, either serves its purpose.

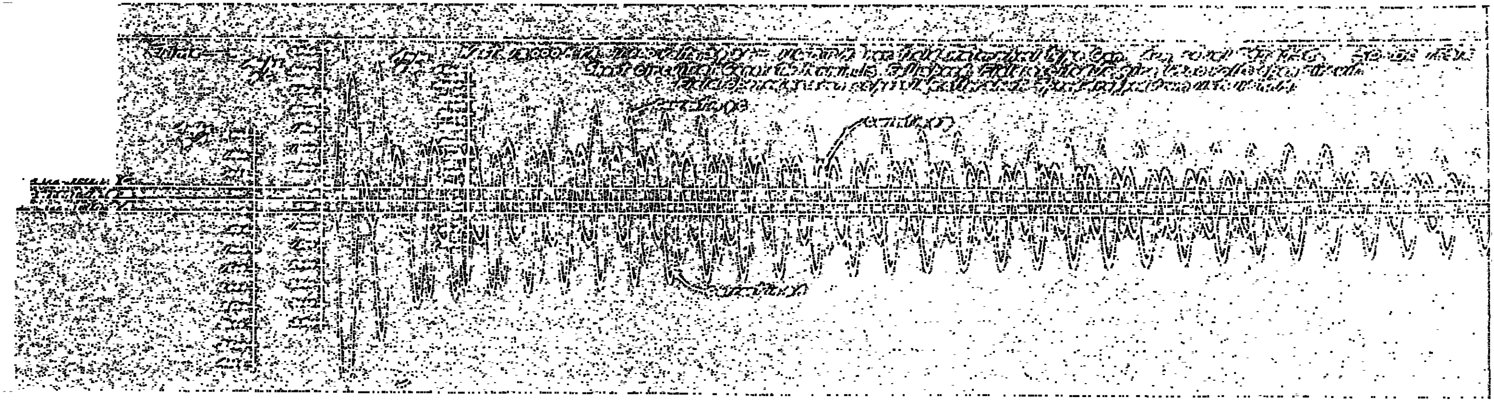
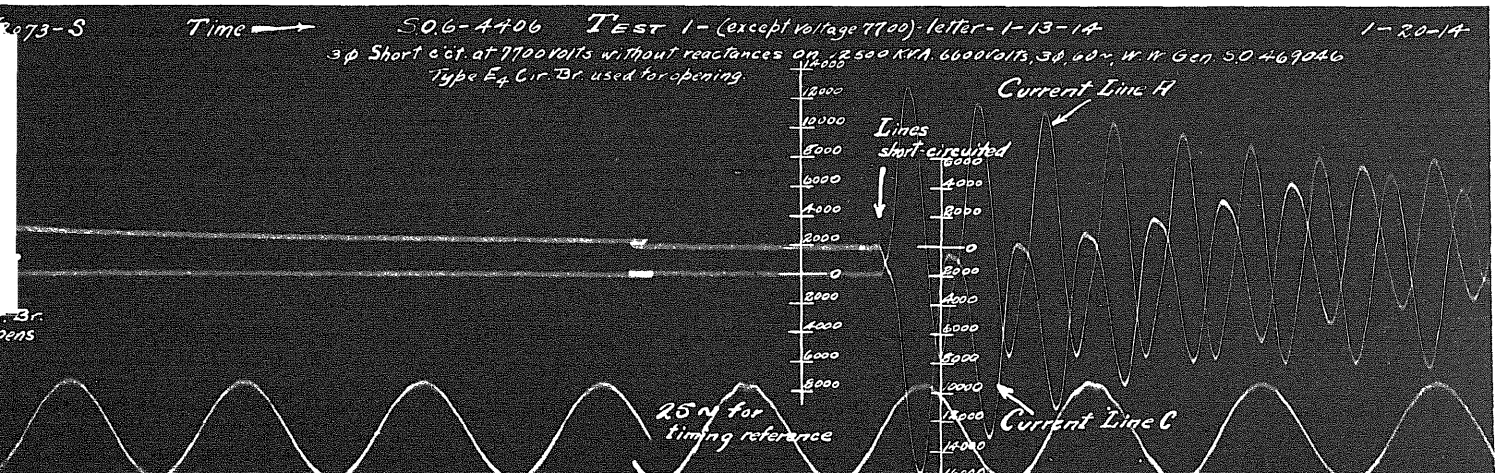


Fig. 24.—Oil Circuit-breaker



While it is not possible to calculate accurately the breaking capacity of an oil circuit-breaker, the capabilities of the apparatus built by the larger makers have been determined fairly closely by tests and experience, so that the ratings assigned may be taken as a basis for selection.

When an alternator is short-circuited the current rush in the first instant is limited only by the inherent or instantaneous reactance of the machine. This excessive current dies down in the course of one or two seconds to a lower value, which the machine can maintain more or less indefinitely. This lower value depends on the synchronous reactance of the generator. If an automatic oil circuit-breaker be called upon to open a short-circuit, it must rupture an excess current, the value of which will depend on the time interval between the occurrence of the fault and the instant the contacts of the circuit-breaker part.

In fig. 24 is an oscillograph record of the currents in the three phases of a water-wheel generator when short-circuited. This machine had a normal rating of 12,000 k.v.a., 11,000 volts (632 amp. per phase), 25 cycles, 116 r.p.m. A study of this will show that in the first half-cycle the current in phase C was approximately 3700 amp., and in the second and third half-cycles 3200 amp., practically symmetrical.

The current in B phase, however, reached about 4300 amp. in the first complete half-cycle, and in the succeeding half-cycle barely reached 1000 amp., this being distinctly unsymmetrical. Similarly in the first half-cycle, current in phase A is off the record, probably about 4500 amp., while in the next half-cycle it is 1000 amp., again unsymmetrical. The lack of symmetry entirely disappears in phase B after 9 cycles, and in phase A after 13 cycles, although after the passage of 0·2 second or 5 cycles, the dissymmetry is almost negligible.

In fig. 25, showing a short-circuit on a 12,500 k.v.a., 6600 volt (1095 amp. per phase), 3-phase, 60-cycle water-wheel machine, it will be noticed that in the first cycle the current in line C is entirely on one side of the zero line, and in A it swings from 13,000 amp. to 6000 amp. in the first period, although by the time the circuit-breaker opened in 9 cycles (0·15 second), both were practically symmetrical.

This lack of symmetry is known as the " doubling effect ", the extent of its occurrence depending on the point in the voltage wave at which the short-circuit occurs. If the doubling effect were to continue until the circuit-breaker contacts part, considerably more energy would have to be dissipated in the arc, since this is a function of current and time.

In fig. 26, an unsymmetrical current wave is analysed. OX represents the zero line, the wave being displaced above the zero until B. The curve AB lies at all points midway between the peaks of successive half-cycles. Such a wave is composed of two elements, a direct component, the distance between curve AB and the zero line, and an alternating component, which is the difference between the peak values lying along CD and the direct values on AB.

The r.m.s. value of such an unsymmetrical current wave at any instant

is the square root of the sum of the squares of the value of the direct component, plus the effective value of the alternating component.

Although in nearly every case the unsymmetrical condition will have disappeared before a circuit-breaker can open, it has been taken into account for the shorter times in the table which follows. In standard British practice, times less than 0·2 second are not considered. The current values used for 0·2 second agree very closely with those given in this American table.

As a rule the inherent reactance of water-wheel driven alternators may be taken at about 20 per cent to 25 per cent, the general shape of the short-

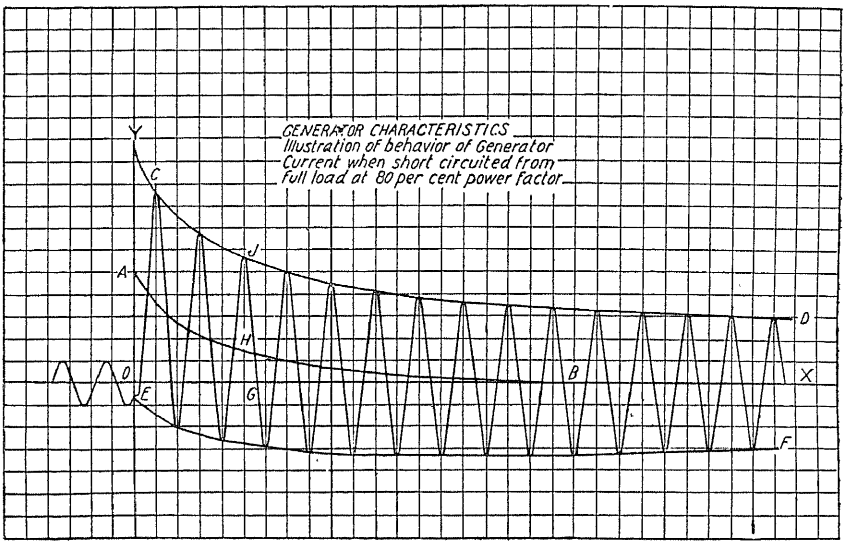


Fig. 26.—Short-circuit Characteristics of Generators

circuit current curve, assuming no external reactance, being as in fig. 27. This curve is often referred to as the "die-away" curve of the machine.

In this case it will be seen that if a circuit-breaker connected to this generator operates in 0·2 second it will have to interrupt four times the normal full load. If its operation be delayed by means of a time-limit device until $1\frac{1}{2}$ seconds have elapsed, the current to be interrupted will only be $2\frac{1}{2}$ times normal full load. Very few oil circuit-breakers will commence to open in less than 0·2 second after the trip coil is excited, and if a relay of any type be interposed this time will be extended at least 0·05 second. Large high-voltage switches are frequently more sluggish in commencing to operate, although the speed when under way is not inferior.

The addition of reactance external to the generator windings still further reduces the short-circuit current. The precise value of current which will pass in a system having added reactance is difficult to determine, but in the table facing are given figures which represent the average values taken from

REACTANCE

Seconds from start of short-circuit.	8%.	10%.	12%.	15%.	20%.	30%.	40%.	50%.	60%.	75%.	100%.	125%.	150%.
	Short-circuit Current Factor.												
0·05	13·91	11·16	9·59	7·68	6·04	4·03	3·01	2·40	2·00	1·58	1·17	0·92	0·77
0·08	11·78	9·54	8·25	6·66	5·27	3·59	2·74	2·21	1·86	1·50	1·13	0·90	0·76
0·10	10·94	8·89	7·68	6·23	4·97	3·41	2·63	2·13	1·81	1·46	1·11	0·89	0·76
0·15	9·16	7·54	6·57	5·40	4·38	3·08	2·42	2·00	1·71	1·41	1·09	0·89	0·76
0·20	8·24	6·80	5·97	4·95	4·06	2·92	2·30	1·92	1·66	1·38	1·08	0·88	0·76
0·25	7·55	6·28	5·54	4·63	3·82	2·79	2·23	1·87	1·63	1·36	1·07	0·88	0·76
0·30	7·03	5·88	5·19	4·39	3·67	2·70	2·18	1·84	1·60	1·34	1·06	0·88	0·76
0·40	6·27	5·30	4·74	4·03	3·40	2·57	2·10	1·79	1·57	1·32	1·06	0·87	0·76
0·50	5·74	4·91	4·40	3·80	3·23	2·48	2·04	1·75	1·54	1·31	1·05	0·87	0·76
0·70	4·99	4·34	3·93	3·45	2·98	2·34	1·96	1·70	1·51	1·29	1·04	0·87	0·76
1·00	4·25	3·77	3·47	3·11	2·73	2·21	1·88	1·65	1·48	1·27	1·04	0·87	0·76
1·50	3·63	3·31	3·08	2·82	2·53	2·10	1·81	1·61	1·45	1·25	1·03	0·87	0·76
2·00	3·20	2·98	2·82	2·63	2·39	2·03	1·77	1·58	1·43	1·24	1·02	0·87	0·76

a large number of cases. This will give a basis for switch selection certainly as accurate as the breaking capacity ratings assigned to the oil circuit-breaker. This table was prepared after a conference between the leading switchgear manufacturers in America, and was given in a paper, "Rating and Selection of Oil Circuit-breakers", by E. M. Hewlett, J. N. Mahoney, and G. A. Burnham, read before the American I. E. E. in 1918. The numbers given are factors by which the normal full load current must be multiplied to get the short-circuit current at any given instant. The percentage reactance figures represent the total reactance in the circuit, including that of the

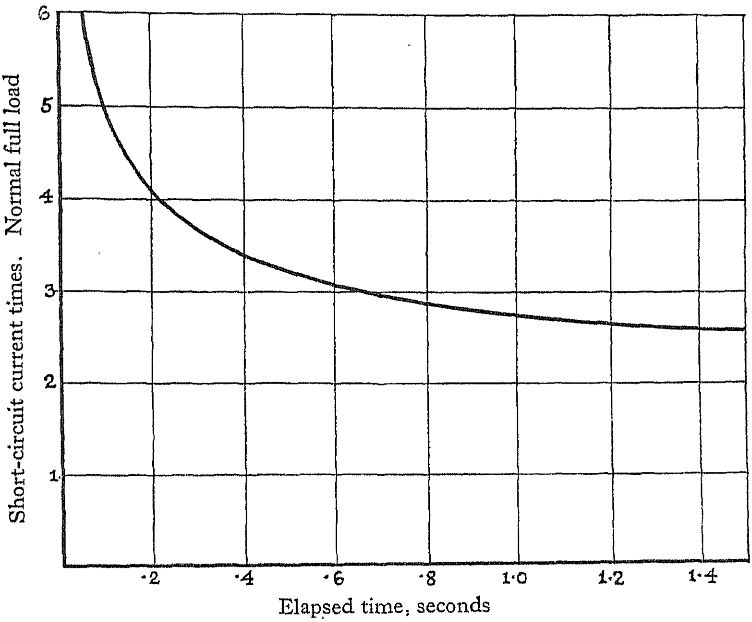


Fig. 27.—Generator "die-away" Curve

generator, up to the point at which the short-circuit takes place. At the shorter time intervals, allowance has been made for possible doubling effect.

In calculating the possible short-circuit current, all synchronous machinery connected to the system must be taken into account, and not merely the total capacity of generating plant. A rotary convertor or synchronous condenser possesses sufficient fly-wheel effect to enable it to supply current as a generator during such times as an oil circuit-breaker requires to operate.

The figures are based on the assumption that at the time of short-circuit the generators are carrying full load at 80 per cent P.F., and that no voltage regulators are used. When voltage regulators are connected, they will tend to hold up the voltage, despite the short-circuit, with the result that the sustained short-circuit current will be considerably increased, probably to

the extent of 50 per cent. The effect is not noticeable, however, in the early stages of the short-circuit.

In using the figures given in the table it is assumed that the fault occurs instantly as a dead short-circuit. This is not always the case, and especially where cable networks are concerned it is quite possible for the fault to develop through an interval of time such that the current is at its peak value when the switch contacts part. For this reason important main feeder circuit-breakers are sometimes selected on the basis of true instantaneous operation. Where only one circuit-breaker per circuit is employed, as is usual in this country, the practice is to be recommended.

A further reason advanced for following this practice on important circuits is that experience has shown it to be much more difficult for a circuit-breaker to operate when closed on an existing short-circuit, than when the short-circuit develops with the circuit-breaker already closed. The fact is indisputable, but it should not be used as an argument for changing the basis of selection, since the standard test for breaking capacity specifies that the circuit-breaker must be capable of opening its rated k.v.a. twice in succession, which implies closing on a possible short-circuit before the second operation.

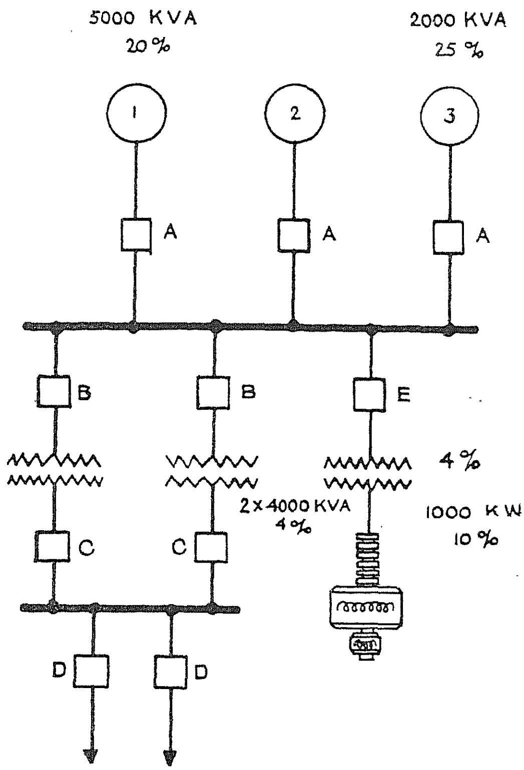


Fig. 28.—Typical System

Certain of the large American systems have lately adopted a semi-automatic arrangement, whereby a substation switch, which trips out on overload, is automatically reclosed, and if it then trips, is again reclosed after a short time interval. The number of reclosures may be as many as nine, with time intervals of from 30 seconds to 2 or 3 minutes. It has been found that the second and subsequent operations are much more severe on the switch than is the first A great deal of research work has been carried out in the past year to determine the ratings which should be applied to circuit-breakers operating a varying number of times in succession. This work has not yet been made public.

Calculation on the basis of percentage reactance is well suited to the

selection of circuit-breakers in the generating station, since in all connected apparatus the reactance is much greater than the resistance. The same holds good in most cases where an overhead transmission line is in the circuit, but where cables are employed, the resistance value is usually greater than the reactance, and calculations must be based on both ohmic resistance and reactance.

When working by the percentage method care must be taken to reduce all values to the same basis of capacity. A reactance which causes a 5 per cent drop in voltage with 200 k.v.a. passing may equally be referred to as giving 10 per cent drop with 400 k.v.a., or $2\frac{1}{2}$ per cent drop with 100 k.v.a.

To make the operation entirely clear a concrete case will be taken, the system being shown in fig. 28. It is generally convenient to take the total generator capacity as the basis. In this case we have:

Machine.	Capacity K.V.A.	Reactance.	Symmetrical Short-circuit.	
			Derivation.	K.V.A
Generator 1 ..	5000	20 per cent	$\frac{5000 \times 100}{20}$	25,000
Generator 2 ..	5000	20 ,,	$\frac{5000 \times 100}{20}$	25,000
Generator 3 ..	2000	25 ,,	$\frac{2000 \times 100}{25}$	8,000
Rotary converter	1000	14 ,,	$\frac{1000 \times 100}{14}$	7,150
Total ..	13,000		Total ..	65,150

This aggregate short-circuit k.v.a. represents approximately 20 per cent reactance with 13,000 k.v.a. of generating plant.

The oil circuit-breakers at B must be of sufficient size to interrupt 13,000 × 4·06 k.v.a., since in the event of a short-circuit across the transformer primary all the plant would supply energy to the fault. The factor 4·06 is taken from the table on p. 177, and assumes a switch operating in 0·20 second.

In the case of circuit-breaker C, the maximum current which it could be called upon to open is that which would pass through one transformer. The transformer is rated 4 per cent at 4000 k.v.a., which is equivalent to 13 per cent at 13,000 k.v.a., giving a total reactance up to the switch of 33 per cent. Referring again to the table of factors, and interpolating, we find this circuit-breaker should be capable of opening 13,000 × 2·75 k.v.a.

If a short-circuit occur on the line side of the feeder circuit-breaker D, current would be supplied through both transformers in parallel. Together these have a reactance of 4 per cent at 8000 k.v.a., or $6\frac{1}{2}$ per cent at 13,000 k.v.a., giving a total reactance to the switch of $26\frac{1}{2}$ per cent on

the 13,000 k.v.a. basis. These switches must be capable of interrupting 13,000 × 3·65 k.v.a.

It will be understood that, in practice, oil circuit-breakers are not built for all these fine graduations in breaking capacity. A single builder will make circuit-breakers with perhaps half a dozen steps from 50,000 k.v.a. to 500,000 k.v.a. breaking capacity, and for a given normal current and voltage.

The proper selection of sub-station circuit-breakers becomes very difficult on a system with an elaborate distribution network, owing to the many changes which can be made in the connections, each of which will vary the available parallel paths for short-circuit current. Several American power-supply authorities have made up models of their electrical system, using resistance coils to represent the various sections of line. A known voltage is impressed across this model, and the division of current gives a direct guide to the breaking capacity required at any point.

Further discussion of this question is out of place herein, but reference may be made to the papers cited below.*

* "An Artificial Transmission Line with Adjustable Line Constants", C. E. Magnusson and S. R. Burbank, *Trans. A. I. E. E.*, Vol. XXXV, p. 1137; "Design, Construction, and Tests of an Artificial Power Transmission Line for the Telluride Power Company of Provo, Utah", G. H. Gray, *Trans. A. I. E. E.*, Vol. XXXVI, p. 789.

CHAPTER IX

Lightning Arresters

The term "lightning arrester" is commonly, but inaccurately, used to cover all devices which are employed to protect the system from the effects of over-voltage or high-frequency transients, no matter to what cause these be due. On account of its convenience this use for the words will be continued in this work.

There is little definite knowledge regarding the characteristics of lightning, nor is this surprising when the difficulties of experimental research are considered. There are clearly wide differences between flashes, but extremely high voltages and frequencies are involved in each type.

Dr. Steinmetz has suggested the following as the probable average electrical characteristics of a lightning flash.

Potential gradient at moment of discharge	= 50,000 volts per foot.
Potential difference between discharge points in the cloud	= 50,000,000 volts.
Current in discharge	= 10,000 amp.
Duration of discharge	= ·00005 sec.
Frequency of discharge	= 500,000 cycles per second.
Energy of discharge	= 10,000 kw.-hr.

It is generally conceded that the frequency is possibly much higher than the estimate quoted, authorities frequently suggesting one or even two million cycles per second.

To the engineer who does not make a special study of the subject a most convincing proof of the extraordinarily high frequency is furnished by the way in which the slightest bend or loop in the run of a lightning conductor will cause a discharge to jump to an alternative and seemingly very high resistance path to ground.

There is no known device which will relieve an electrical transmission system from the effects of a direct stroke of lightning. Fortunately a direct stroke is rare, and when it does occur the immediate failure of the adjacent insulators usually saves the rest of the system from effects which cannot be relieved by the protective apparatus installed.

In modern practice transmission lines are usually run with a ground wire above all conductors, this ground wire being earthed at every pole. This has proved of very great benefit, so much so, in fact, that a few systems are operating with no other protection. A high factor of safety on all insulation

is an obvious step towards eliminating over-voltage troubles, but here caution is necessary. It will not pay so to insulate the transmission line as to make the high-voltage transformers the weakest link, since a line insulator is much more easily and cheaply replaced.

When lightning discharges from cloud to cloud, it is possible for a high-frequency high-voltage current to be induced in a transmission line, although this occurrence is considered to be uncommon.

The more usual effect is due to the presence of a cloud which is electrostatically charged, and which induces in the line a corresponding and opposite charge. If the cloud then discharges, the line charge is freed, and travels along the line until it either finds a discharge path to earth or (on a very long line) until it is dissipated by partial leakage across all the insulators it encounters. At the point of liberation such a wave is characterized by a very steep wave front.

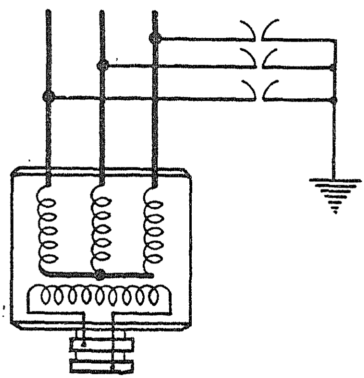


Fig. 1.—Elementary Lightning Arrester

Switching operations on high-voltage lines and transformers usually give rise to high-frequency surges of more or less severity. As a rule these are not sufficient to destroy the insulation of apparatus.

The breakdown of an insulator, which results in what is termed an arcing ground, will set up high-frequency oscillations which are particularly destructive in their effects, since resonance is commonly caused at some point or points in the system.

All of the effects enumerated are characterized by extremely high frequency, although the amplitude of the induced voltage waves may vary widely.

The function of the lightning arrester is to by-pass to earth these high-voltage high-frequency surges from the line or connected apparatus. The arrester is therefore connected in shunt between line and earth in the manner indicated in fig. 1. Simply connected in this way, it is by no means certain that the arrester would immediately discharge and relieve the system. It is more probable that the wave would pass right along to the first transformer or connected machine, and, there meeting impedance, would be reflected and pile up to such a voltage as to puncture the insulation.

With the very high frequencies encountered the voltage wave would not penetrate beyond the first few turns of a transformer winding, since these would present very high impedance. In modern practice the end turns, to the extent of perhaps 5 per cent, are specially heavily insulated to withstand these over-voltages. Frequently the impedance of the end turns alone is relied upon to reflect the voltage wave back to the lightning arrester where it is discharged to earth.

More usually a choke coil, consisting of several turns of bare copper rod supported on insulators, is put in the circuit between the arresters and the apparatus protected (fig. 2). The reactance of this choke coil is suffi-

ciently high to ensure that high-frequency surges are reflected and do not pass to other apparatus, while at the normal system frequency it is negligible.

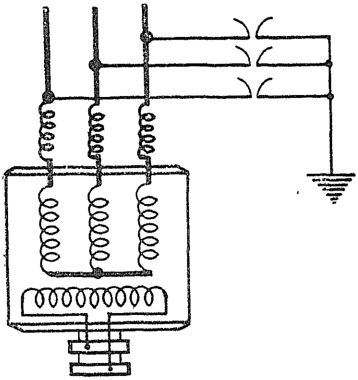


Fig. 2.—Elementary Lightning Arrester with Choke Coils

The utmost care must be taken to locate arresters as close to the end of the transmission lines as possible, and to avoid bends or turns in the conductors which might serve as points at which the wave would be reflected, pile up, and break down the insulation, instead of being discharged through the arrester. For this reason the practice of connecting arresters to the bus-bars of a system is to be condemned, since it is almost impossible to avoid the introduction of some such point of danger. The desire to offer an attractively low price may on occasion induce a contractor to offer such an arrangement. The only correct method, however, when arresters are used, is to install one at each end of every overhead transmission line, in front of all connected apparatus or machines.

In high-voltage work the ideal arrangement can best be attained by placing both choke coils and lightning arresters outside the station. In fig. 3 is

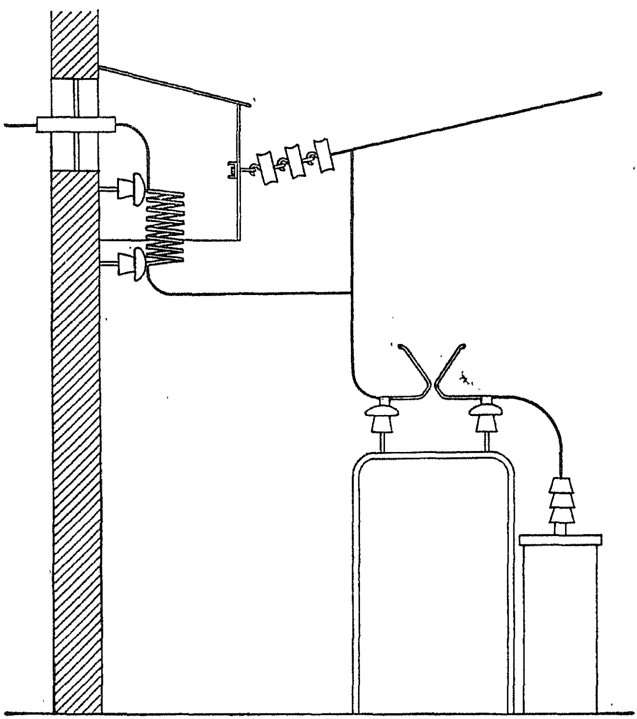


Fig. 3.—Ideal Location for Choke Coils and Lightning Arrester

illustrated such an arrangement. It will be noticed that the choke coil is inserted in such a place that there is a minimum length of conductor, and no insulators between it and the arrester, and that the latter has a direct connection to the line.

In general it is assumed that as all apparatus is built to withstand a test voltage of at least twice normal, adequate protection will be afforded by a device which will by-pass pressures in excess of this. The ideal condition would be to have a by-pass circuit which would relieve the system of all voltage waves or impulses exceeding normal amplitude or frequency, but in most cases this is impracticable. The lightning arrester is consequently set for a spill-over voltage of about 150 per cent to 180 per cent normal line voltage. It is of course necessary for this value to be so much less than the spill-over or breakdown voltage of the line or transformer insulation as

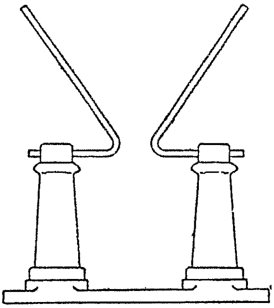


Fig. 4.—Simple Design of Horn

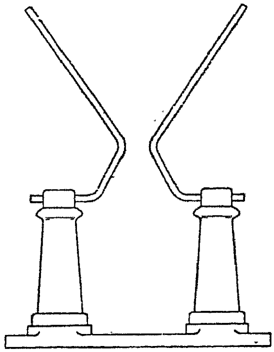


Fig. 5.—Horn with raised Gap to increase initial Blow-out Effect

to ensure that over-voltages will discharge to earth through the appointed device and not elsewhere.

One of the earliest forms of lightning arrester was the horn gap, devised by engineers of Siemens & Halske in 1896, and this is even to-day an essential part of the majority of lightning arresters. It was discovered that with metal horns of certain characteristic shapes, an arc could not be maintained, but would travel towards the ends of the horns, until it became so attenuated as to go out. This effect is not due entirely to convection currents in the air. The first experiments were made with horns shaped as in fig. 4. Later tests, with horns as in fig. 5, showed that an arc was more quickly disrupted, indicating that the effect was mainly magnetic, the loop formed between the lower ends of the horns and the arc, tending to embrace as large an area as possible, in the manner now well understood in relation to flexible circuits. With the first form of horn, in which the nearest points were at the bottom, convection undoubtedly started the arc upward, and thereafter co-operated with the magnetic effect in elongating it.

As stated above, the ideal arrester would be one in which the over-voltage wave or impulse is by-passed directly to ground. The arrangement in the case of a horn arrester would then be as shown in fig. 6. Although the horns

may be set so far apart as to require perhaps twice normal voltage to jump the gap and form an arc, yet as soon as such an arc is formed, the surrounding air becomes virtually a conductor and the normal line voltage will suffice to maintain the arc. Consideration will at once show that if an arc occurs on a single horn in the case of a system with earthed neutral, or on two horns simultaneously on an insulated neutral system, a short-circuit path is at once provided for current to flow from the power system.

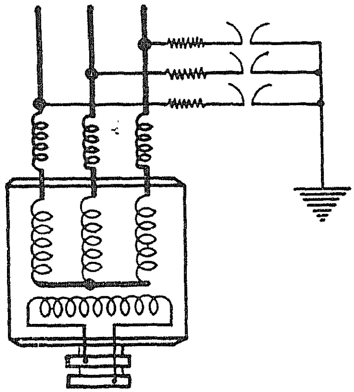


Fig. 6.—Correct Location of Series Resistance

If this power arc only persisted a few cycles, and were then broken by the horns, it might not be particularly objectionable, but in point of fact the arc may persist for a considerable time before rupture. A horn gap is only capable of rupturing arcs of quite small current, certainly not in excess of 10 amp. This value is considerably reduced if the gap is small, so as to cause it to spill-over at a voltage nearer to normal. It therefore becomes essential to provide a resistance in series with the horns to limit the flow of power current following an arc over.

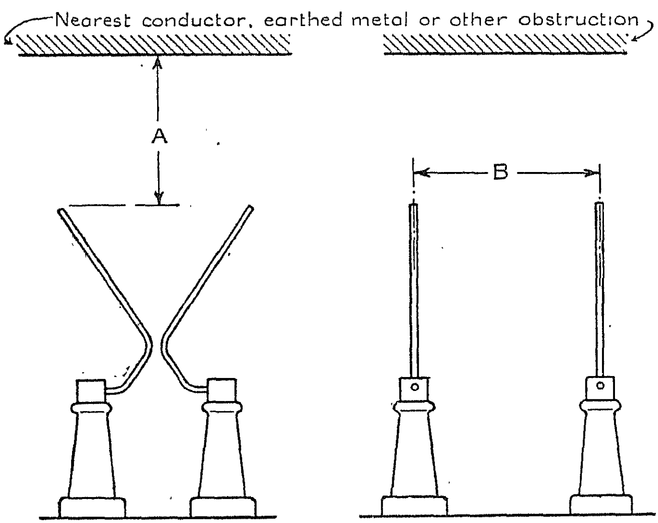


Fig. 7.—Clearances for Horn Arresters

If the series resistance be high, the efficiency of the device as an arrester is affected, since there will be a voltage drop across the resistance itself, which may conceivably exceed the breakdown voltage of the system insulation under certain conditions.

The selection of a value for the resistance is therefore a matter for compromise, the value generally adopted being such as will limit the power current to between 1 and 5 amp. with normal voltage impressed.

The resistance should be connected on the line side of the horns as in fig. 6, and not between horns and earth, since should the arcs from adjacent horns be blown together, a short-circuit would occur. It should be understood that the arc rises far above the horns, and in this position is easily deflected by light currents of air. The minimum clearances (fig. 7) which it is desirable to use are tabulated below.

Volts.	Indoors.		Outdoors.	
	A.	B.	A.	B.
6,600	30 in.	16 in.	50 in.	24 in.
11,000	36 in.	20 in.	60 in.	36 in.
25,000	48 in.	24 in.	72 in.	42 in.
35,000	60 in.	30 in.	84 in.	54 in.
50,000			120 in.	70 in.
66,000			160 in.	85 in.
88,000			210 in.	105 in.
110,000			260 in.	120 in.

The resistance employed must be non-inductive, if it is of the wire-wound type. Water pots, wire (usually oil-immersed), carborundum, and built-up resistance materials of a similar nature are all used. The aim in selecting the resistance material is to obtain high thermal capacity, since this will enable the arrester successfully to discharge through a longer period of time. Water pots and oil-immersed metallic resistances are the best from this angle, but they are bulky, and in addition the former require some attention in replacing water lost through evaporation. The various forms of resistance rods are cheap and compact, but are rather apt to disintegrate under passage of heavy currents.

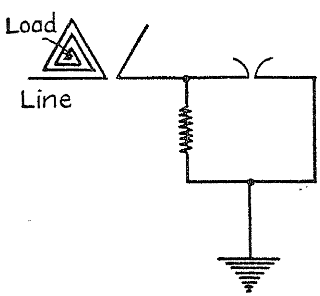


Fig. 8.—Diagram of "Burke" Arrester

There are several forms of arrester which are modifications in some degree of the horn and resistance device. Space does not permit the description of these in detail, since each enjoys only a limited popularity as compared with the simple horn and resistance.

One modification which deserves notice, however, is the Burke arrester, which is very widely used in the United States, in situations where low first cost is of prime importance. From the illustration, fig. 8, it will be seen that the choke coil is triangular in form, one side being utilized as one of the horns. An impulse travelling in from the line meets its first obstruction right at the gap, which is the ideal situation in an arrester. It is found that

this design of arrester is appreciably more sensitive than is a horn with the usual helical choke coil mounted separately. A small supplementary horn and resistance is used, this giving in a measure the effect of a low-equivalent multi-gap arrester, a type which is described hereafter.

The gap necessary to secure spill-over at any voltage varies with the altitude above sea-level, a larger gap being necessary as the height increases. The spill-over voltage may be closely approximated by multiplying the figure at sea-level by the ratio between the air density at sea-level and at the altitude under consideration. The Standardization Rules of the American Institute of Electrical Engineers give the following table of correction factors to be applied when testing.

AIR DENSITY CORRECTION FACTORS FOR SPHERE GAPS

Relative Air Density.	Diameter of Standard Spheres in Millimetres.			
	62·5.	125.	250.	500.
0·50	0·547	0·535	0·527	0·519
0·55	0·594	0·583	0·575	0·567
0·60	0·640	0·630	0·623	0·615
0·65	0·686	0·677	0·670	0·663
0·70	0·732	0·724	0·718	0·711
0·75	0·777	0·771	0·766	0·759
0·80	0·821	0·816	0·812	0·807
0·85	0·866	0·862	0·859	0·855
0·90	0·910	0·908	0·906	0·904
0·95	0·956	0·955	0·954	0·952
1·00	1·000	1·000	1·000	1·000
1·05	1·044	1·045	1·046	1·048
1·10	1·090	1·092	1·094	1·096

The curve, fig. 9, gives the relation between air density and altitude.*

In the table below are given figures showing usual gap settings adopted between horns at sea-level, these corresponding to a spill-over voltage of about 150 per cent normal. Gap settings must be adjusted to suit each particular installation, since humidity as well as altitude will affect the spill-over voltage, and, moreover, variations in the form of electrode may cause considerable differences.

Normal Volts.		Gaps.	Normal Volts.		Gaps.
10,000	....	$\frac{1}{2}$ in.	30,000	....	$2\frac{1}{4}$ in.
15,000	....	1 ,,	40,000	....	$3\frac{1}{8}$,,
20,000	....	$1\frac{5}{8}$,,	50,000	....	4 ,,
25,000	....	$1\frac{3}{4}$,,	60,000	....	$4\frac{3}{4}$,,

* F. W. Peek, Jr., *Dielectric Phenomena in High Voltage Engineering.*

Installations in continental Europe are usually protected with horn apparatus, sometimes used in conjunction with condensers or water jets. The severity and duration of lightning storms varies considerably throughout the Continent, but in general the lightning arrester equipments operate satisfactorily. It is interesting to note that simple horns and resistances are widely and successfully used in the Transvaal, where lightning conditions are probably more severe than in any other part of the world.

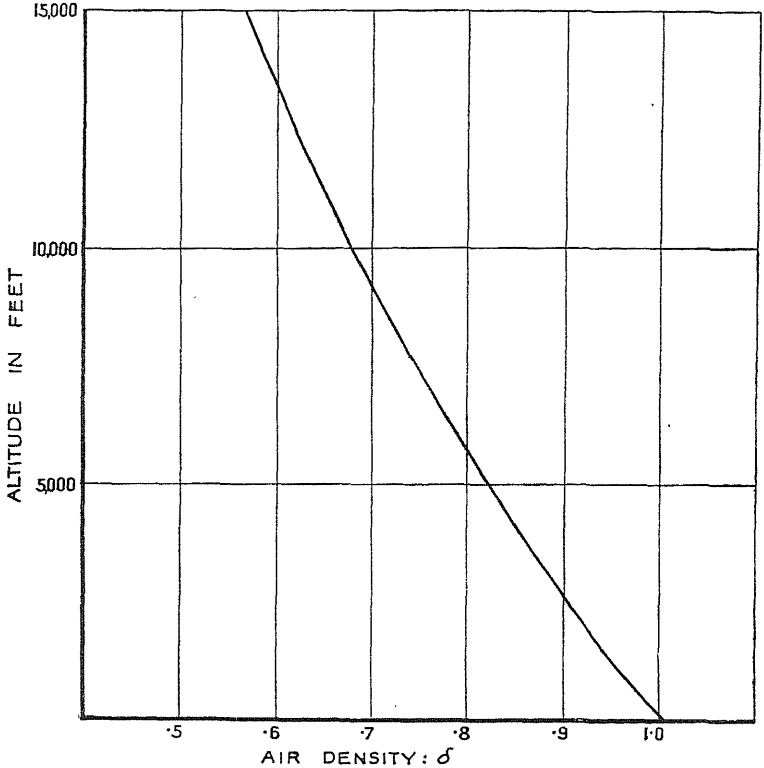


Fig. 9.—Relation between Air Density and Altitude

Mr. Wurtz, an engineer of the American Westinghouse Company, established the principles of the non-arcing metal multiple-gap arrester, with numerous forms of which his name is still associated. The form is also known as the multiple-gap or the low-equivalent lightning arrester.

It is difficult to maintain an A.C. arc between electrodes made of certain alloys of zinc, since zinc vapour has a rectifying effect, and operates to prevent the reversal of current. Hence there is a tendency to suppress the arc every cycle. As in the case of the horn arrester, there is a current limit, although a much higher one, beyond which the arc will be maintained, despite the quenching action, so that limiting resistances must be employed in most instances.

Mr. Wurtz employed several cylinders of his non-arcing metal, so arranged as to form many small spark gaps in series. This amounts to connecting several condensers in series between line and earth (fig. 10). A charge is induced on the cylinder next the line, and this charge in turn is partly expended in charging the adjacent cylinder and partly in the capacity to earth, and so in succession to the last cylinder which is connected to earth, and which will have the least charge. There will thus be a regular gradient in the potential across the gaps, from the line to earth, the gradient being steepest next to the line. If a rise in voltage occurs sufficient to cause breakdown across the first gap, the potential across all other gaps increases, since the full voltage is divided across fewer gaps. The gaps consequently break down in quick succession. A series of gaps arranged in this manner will spill over at a much lower voltage than would a single gap interposing the same total air space. The multi-gap arrester is thus more sensitive to minor voltage surges than is the horn type.

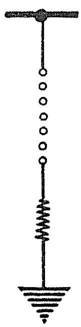


Fig. 10.—Elementary Wurtz Arrester

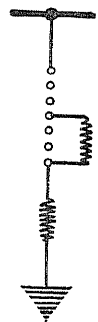


Fig. 11.—Low-equivalent Arrester

The limiting resistances, which are usually of the rod form, are connected some in parallel with a portion of the gaps, and some in series between the last gap and earth (fig. 11). When an over-voltage arc is formed between the cylinders, power current tends to follow, but being opposed by the rectifying action of the zinc vapour, passes to ground through the resistances, which keep it to such value as can be quenched in the first unshunted gaps.

This form of arrester can be built so that power arcs of 20 amp., following on a discharge, can be broken in the first half-cycle, and, as stated above, it can be set to operate at a much lower voltage than a horn. The space occupied is considerably less, but it is usually more costly, especially for the higher line voltages.

Minor voltage surges, although within the test limits for the insulation of apparatus, are nevertheless distinctly objectionable. Moreover, with a system which is completely insulated, local atmospheric conditions may raise the potential of the system as a whole with reference to earth, although the potential from line to line remains normal. To relieve the system of such conditions, water jets are commonly used in conjunction with the horn arresters on Continental installations. These consist simply of a fine column of water which is kept constantly playing on each line. A high-resistance path to earth is thus provided, the section and length of the water column usually being such as will limit the normal leakage current to about one ampere. On a high-voltage system a considerable amount of power thus goes to waste in the course of the year, to obtain protection which is only slightly superior to that which could have been obtained with the multi-gap arrester, and by earthing the system neutral, either solidly or through a resistance.

In another arrangement the horn arrester is supplemented by condensers connected between each line and earth. A voltage surge charges the condenser, which in turn discharges, and gradually dissipates the charge. To prevent overheating of the condenser, a small gap is placed between it and the line, so that the normal line voltage is just not high enough to jump across and charge the condenser each half-cycle. The low thermal capacity of such condensers has limited their application to a narrow field. The tendency now appears in favour of taking a chance with minor voltage surges, and omitting both water-jet and condenser devices.

In American high-voltage work the electrolytic arrester is predominant, and is built in similar forms by both the Westinghouse and General Electric Companies. The action of the electrolytic arrester is based on the characteristics of a film of aluminium hydroxide when formed on a plate of aluminium and immersed in certain electrolytes. Such a film presents a very high resistance to currents of usual commercial frequencies and below a certain critical voltage. Above this voltage the film breaks down, leaving only the low resistance of the electrolyte in the circuit. The instant the voltage drops below critical, the film re-forms and interposes its high resistance, thus preventing the flow of power current following a high-voltage discharge.

The value of the critical voltage depends on the character of the electrolyte used, that at present adopted by the Westinghouse Company, giving a critical voltage of approximately 420, and by the General Electric Company, 330 volts.

As the aluminium hydroxide film is practically an insulator lying between the aluminium plate and the conducting electrolyte, the complete device acts as a condenser on low-voltage but high-frequency impulses, discharging them to earth. As the flow of current through a condenser varies as the frequency, there is increased freedom of discharge as the impulse frequency increases.

In practice these electrolytic arresters are built up of a series of aluminium trays nested one within the other, but kept out of electrical contact by small porcelain spacers. Electrolyte is poured into each tray so as to make contact from one to the next, and the whole stack of trays is immersed in oil. The oil serves the double purpose of increasing the thermal capacity of the device, and of preventing evaporation of the electrolyte.

Horn gaps are placed in series with the trays so as to prevent the constant passage of a leakage current which would heat the electrolyte unnecessarily. The film of aluminium hydroxide dissolves slowly in the electrolyte, but is easily re-formed by the momentary passage of current through the arrester. This charging process, as it is termed, is generally carried out once a day, or in very hot weather, when electrical storms are frequent, twice daily. Recent research has produced some electrolytes the film of which will remain good for possibly a week.

Charging is simply accomplished by short-circuiting the horn gaps. If by any chance the film has been allowed to dissolve entirely, there is a very heavy current rush at the instant of charging, this rush having many of the

undesirable characteristics of an arcing ground. Limiting resistances are therefore placed in series with the charging switch, to keep the current down to a reasonable value.

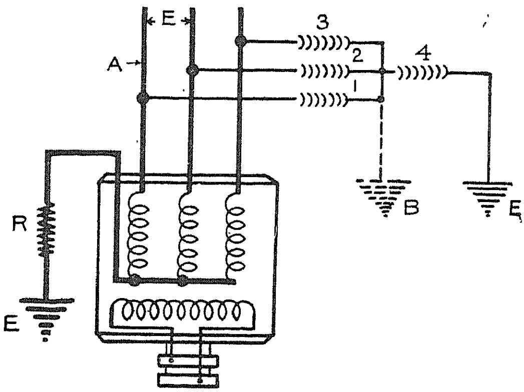


Fig. 12.—Connection of a Four-leg Arrester on a Three-phase System

A point in the application of lightning arresters of the electrolytic and low-equivalent types, which is frequently misunderstood, is in the practice followed on systems having the neutral earthed through a resistance. Imagine first a system (fig. 12) with the neutral solidly earthed (resistance R = 0) and with three stacks of trays, 1, 2, and 3, all earthed at B. In this case, no matter what the condition of the line insulation, the maximum voltage which can normally be impressed across any stack of trays is E/1·73.

If the neutral point be insulated (R = infinity), then with correct line insulation the normal voltage across each stack will still be E/1·73. If No. 1

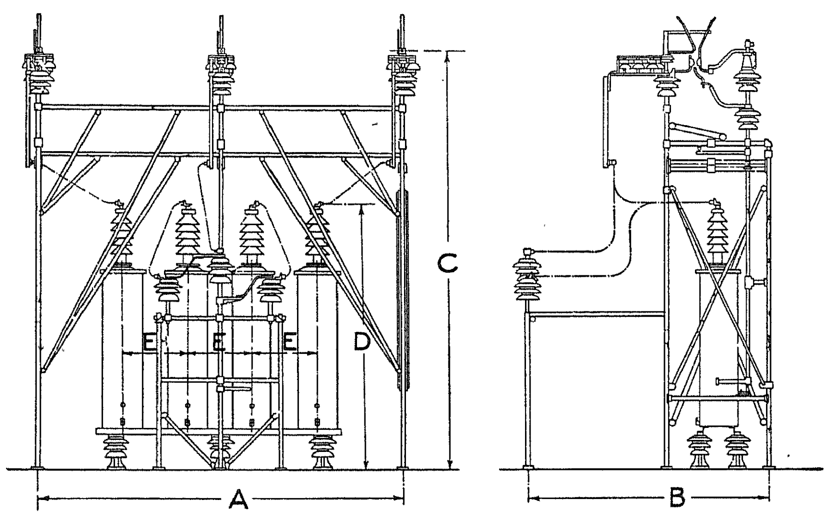


Fig. 13.—Outline of Typical Electrolytic Arrester

line goes to earth at A, however, the voltage across stacks 2 and 3 at once becomes E. With a properly proportioned arrester this should cause them to discharge, although no dangerous over-voltage exists. To take care of such conditions, leg 4 is added between the common point and earth, thus giving the same number of trays between line and line as between line and

earth. With R of some intermediate value, the precise voltage impressed across each leg of the arrester depends on the earth current. To guard against mishap it is customary to use the four-leg arrangement in all cases except where the neutral point is solidly earthed.

When using a four-leg electrolytic arrester, it is necessary to have a transfer switch to interchange electrically the ground leg with one of the other three. When charging, current cannot pass through the ground leg, and the film on this would consequently not be renewed, unless it could be connected direct to the line. The charging operation is thus carried out in two steps.

The electrolytic arrester (fig. 13) may be installed either indoors or outside, the latter practice being almost invariable on very high voltage. In some cases the horns and charging switches are outside and the tanks of electrolytic cells with their transfer switch inside. The idea is to keep the tanks from the direct rays of the sun, the heat of which would accelerate the deterioration of the film.

The arrangements adopted vary to some extent with the different voltages and manufacturers, which accounts for certain apparent discrepancies in the dimensions tabulated below. All dimensions are given in inches, and are sufficiently near to enable preliminary lay-out drawings to be prepared.

Maximum Line Volts.	A.	B.	C.		D.		E.
			In.	Out.	In.	Out.	
15,000	100	60	—	125	—	52	20
25,000	100	85	130	130	92	68	20
37,000	120	85	146	146	92	84	25
46,200	141	85	158	168	95	130	30
50,000	141	85	160	168	98	133	30
69,300	190	124	199	215	133	130	34
73,000	190	124	200	215	136	133	34

Recent research has shown that for a given gap there is a wide variation in the voltages required to arc over between electrodes of different shapes, and further that variations in frequency or steepness of wave front will affect these voltage values in different degrees. With any particular set of electrodes the relation between the voltage at impulse frequency, say 500,000 cycles per second, required to cause a spill-over and that necessary at commercial frequency is termed the " impulse ratio ". Much of interest has been written on the subject and in particular reference may be made to two papers by Mr. F. W. Peek, Jr., " The Effect of Transient Voltages on Dielectrics ", *Trans. American I. E. E.*, Vol. XXXIV, p. 1695, and " Lightning ", *General Electric Review*, p. 586, July, 1916.

These investigations showed that the spill-over voltage between sufficiently large spheres in air is substantially independent of the frequency, i.e. the impulse ratio is unity. Between needle points, however, a considerably

higher voltage is necessary to cause a spill-over at very high frequencies than with normal frequencies, thus making the impulse ratio more than unity. It was found that the sphere diameter bears a definite relation to the air-gap, if the impulse ratio is to remain unity, a reduction in sphere diameter causing the ratio to approach more and more the condition with sharp points.

The impulse ratio between needle points is of the order of 1·5 to 2·3. The horns used for lightning arresters for mechanical reasons are made of round material, perhaps ½ in. or more in diameter. With very small gap settings the device will have sphere characteristics or approximately unity impulse ratio. With larger gaps the impulse ratio will be high.

In the papers quoted it was shown that the impulse ratios for the usual types of suspension insulator vary between 1·2 and 1·6, while for the pin type insulators the figures are about 1·3 to 2·3. With solid dielectrics the impulse ratio is generally higher than with air. Thus varnished cloth or oiled presspahn between flat discs and immersed in oil showed an impulse ratio of from 2·2 to 2·5.

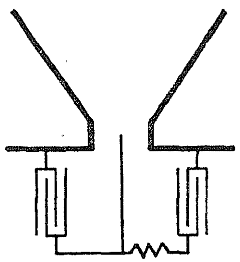


Fig. 14.—Elementary Diagram of Impulse Gap

It will be clear that an arrester in which a sphere gap is employed will have a greater protective action than one embodying a horn which approximates to a needle gap, since high-frequency waves or steep-fronted impulses will be discharged at the same voltage as over-voltages at normal frequency, and in a shorter time than that required to cause a spill-over through the solid insulation of a transformer or across a line insulator. Such conditions of discharge are of the greatest value, since the constant "battering" of high-frequency waves will in time cause the breakdown of transformer insulation, even though the first impact may not do so. Horns fitted with sphere gaps are now standard features in the high-voltage electrolytic lightning arresters.

In a paper, "Lightning Arrester Spark Gaps", by Chester T. Allcutt, *Trans. American I. E. E.*, Vol. XXXVII, p. 833, is described a modified form of sphere gap which is selective in its action, i.e. which will discharge steep-fronted waves more readily than those of normal frequency.

The basic idea is shown by the diagram of fig. 14. The resistance is of such value that at normal frequency the impedances of the two paths are proportional to the respective discharge voltages of the gaps which they shunt. The impedances vary differently with changes of frequency, so that a high-frequency impulse will cause one impedance to become much greater than the other, causing the major part of the potential to be impressed across the resistance. This half of the gap breaks down, putting the full potential across the other half, which immediately breaks down also.

The curve, fig. 15, taken from Mr. Allcutt's paper, shows the advantage gained in a specific instance.

A neat method has been worked out for constructing this impulse gap, shown in fig. 16. It will be seen that the capacity of the insulators supporting

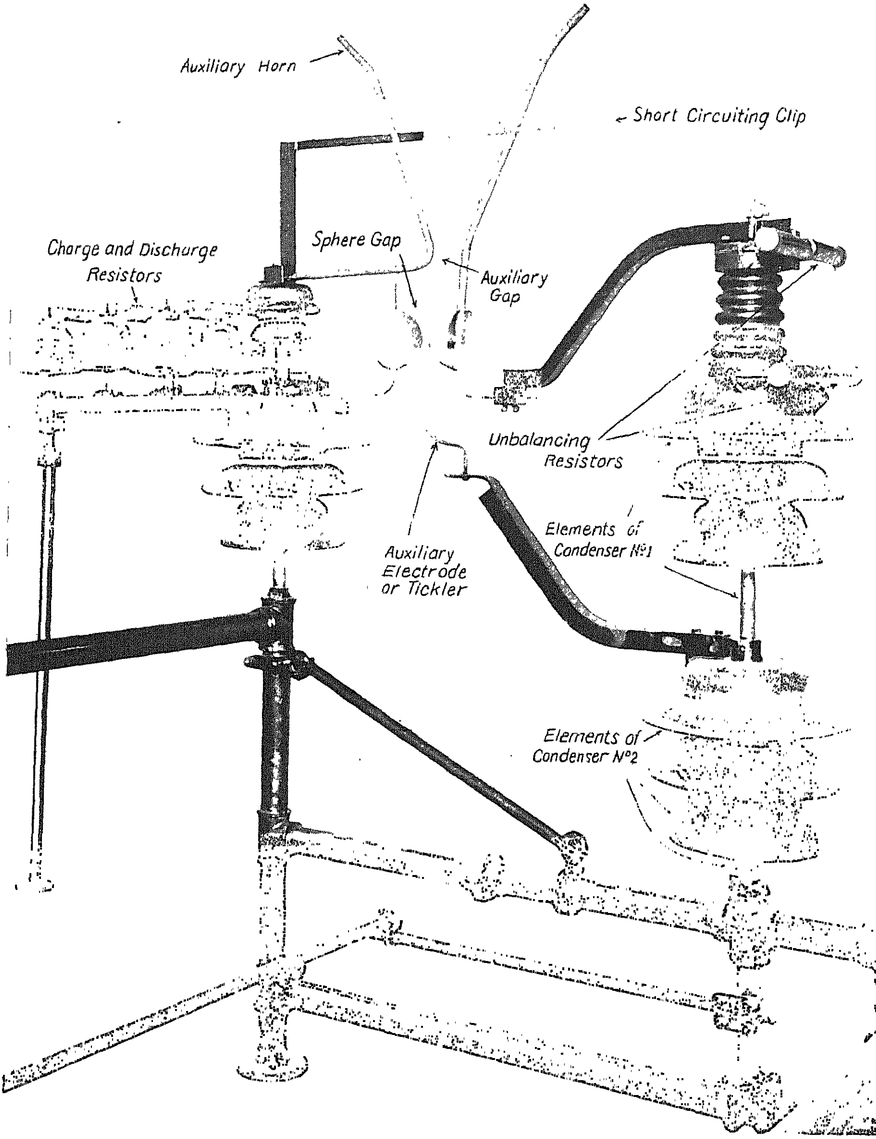


Fig. 16.—IMPULSE GAP FOR ELECTROLYTIC ARRESTER

one of the horns has been utilized; a construction which is both inexpensive and reliable.

Papers read before the American I. E. E. in 1918 by Dr. C. P. Steinmetz and Mr. Crosby Field introduced a new form of arrester known

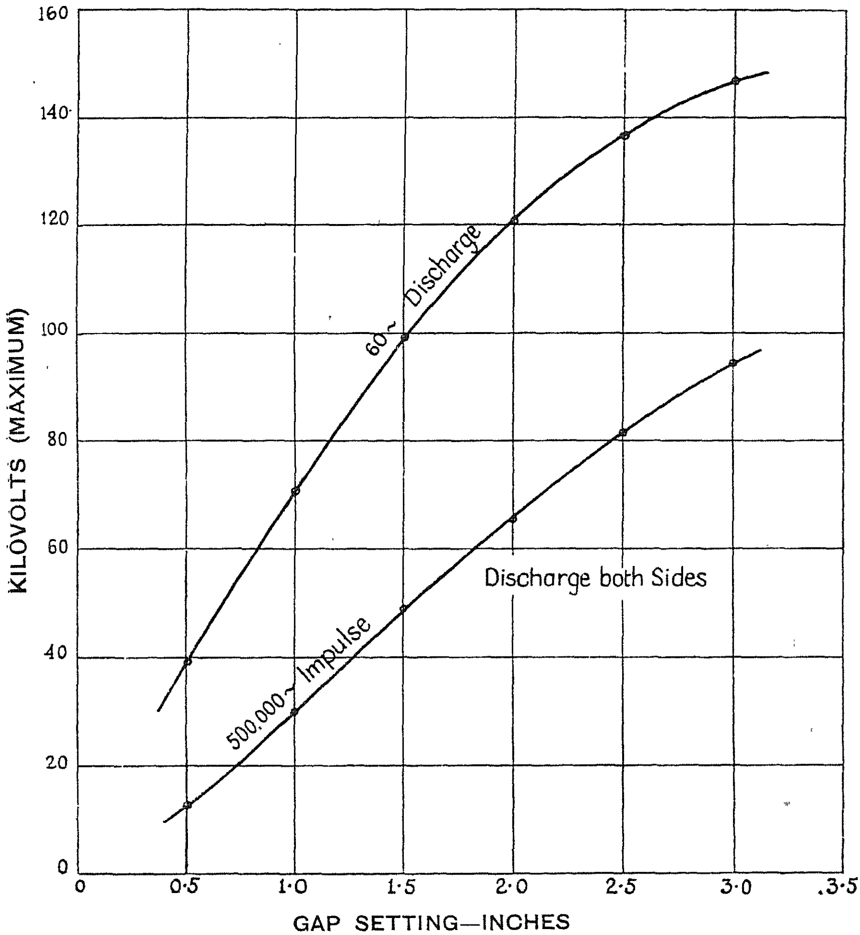


Fig. 15.—Discharge Curves of Impulse Protective Gap, 6·25 cm. Spherical Electrodes mounted on Horns

as the oxide film type. To date this device has only been applied in a very few cases, on systems up to about 60,000 volts.

In construction the arrester somewhat resembles the electrolytic, the cells of the latter being replaced by a series of oxide film units. Each unit comprises a thin porcelain ring on each side of which is a disc of varnished sheradized steel. In the space between the steel plates is a layer of lead peroxide. Lead peroxide is a good conductor until heated to about 150° C., when it changes to a lower oxide which is an insulator.

Above a certain critical voltage the varnish film is pierced, and permits a discharge to ground. The passage of current heats the lead peroxide and reduces it at the point of puncture, thus filling the hole with an insulator and interrupting the discharge.

This device presents certain apparent advantages, particularly in that it does not require periodical charging, but experience with it is yet too limited to determine whether or not it is a sound commercial design.

CHAPTER X

Switchgear Lay-out

Lay-out of switchboard; cubicle structures; high-voltage arrangements

1. Lay-out of Switchboard.—Control of all the generators in a power station should be concentrated at a single switchboard. As a rule this is located in, or immediately adjacent to, the main generator room, but this is not essential. In fact such practice is only desirable in smaller stations where the shift engineer also acts as switchboard attendant.

At times of trouble, perhaps during a severe electrical storm over some part of the transmission system, it is best for the switchboard operator to be away from all the attendant sudden noises in the generating-room, which may affect his nerves and judgment at a critical moment. It is becoming more and more the practice in large plants to have both switching apparatus and control in a separate building. The " control " or " system " engineer's station on a large network with several generating plants is almost always apart from the power stations.

If control is to be isolated in this manner, it follows that all connected machinery must be protected automatically, since the switchboard instruments will not necessarily indicate trouble to an operator who can neither see nor hear the machine he controls.

Wherever the main switchboard is placed, provision must be made so that the water-wheel speed and the generator excitation can be controlled from the same point. It is not necessary as a rule to be able to start up a machine from the switchboard, although in some plants this is arranged for in addition to the usual hand control on the generator room floor. Each governor is fitted with a small operating motor, usually D.C., so that the necessary equipment on the control desk is a simple, small double-throw switch to start, stop, and reverse this motor.

Where a main field rheostat is required for the generator, it is usually convenient to operate this from a distance, either by means of sprocket and chain drive, as is the general European practice, or by a servo-motor when the current to be handled is so large as to make hand operation too heavy. In either case it is essential so to locate the rheostat as to secure adequate ventilation. An exciter field rheostat is a much smaller piece of apparatus, and it is often possible to mount it immediately behind the control board.

In determining the position of the main field rheostat, careful consideration has to be given to the run of conductors between it and the generator.

From this point of view, servo-motor control is preferable, since the rheostat can be near the generator without complicating the control. Mechanical drive necessarily limits the rheostat position. In the figs. 1 and 2 are indicated possible locations which can be used while employing handwheel and chain operation. The method of drive shown is almost invariably adopted in this country when remote control is necessary. Continental practice inclines towards the use of wire rope, connecting short lengths of driving chain, which is certainly much more flexible in the matter of location, and is easier to install.

It is common American practice to install an ammeter in each phase of every circuit controlled from the main switchboard. This is an unnecessary

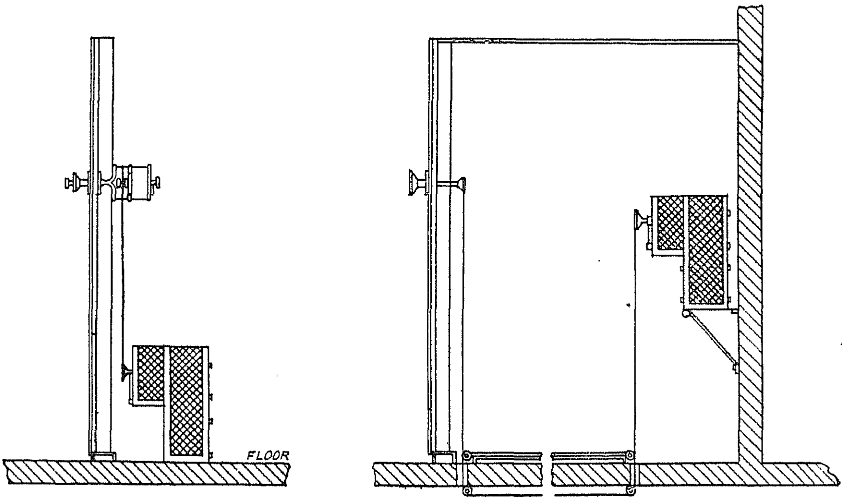


Fig. 1.—Chain Drive to Rheostats at Rear of Switchboards

complication, since the loading of the phases may reasonably be expected to be balanced within the limit of error on a commercial ammeter. An alternative method is to use a single ammeter worked in conjunction with a "jack" by which it can be connected to the series transformers in any one of the three phases. This is positively objectionable, in that potential points of bad contact or even of open-circuit are introduced into the series transformer secondary, without serving any useful purpose.

The only extra contacts which should be put in the secondaries of series transformers are removable links to permit test instruments to be inserted without disturbing the wiring to permanent instruments. Such links should be arranged so that the test instrument must be connected before the link can be removed. This is necessary to avoid open-circuiting the secondary, the full-load open-circuit voltage of which is sufficiently high to be dangerous.

Such testing terminals are of great importance, since they facilitate testing the operation of apparatus on which the safety of the plant depends. From the relay man's point of view the ideal way of testing his protective

relays is to reproduce deliberately the faults against which the relays are supposed to protect. Practically this is out of the question, and the next best thing is to make it easy to check the movement of the relays alone.

On systems having long transmission lines, the generators may be run over-excited, or an otherwise idle machine may be run as a synchronous condenser, to counterbalance the effect of line reactance. Each generator is therefore equipped with a power factor meter, showing both lag and lead.

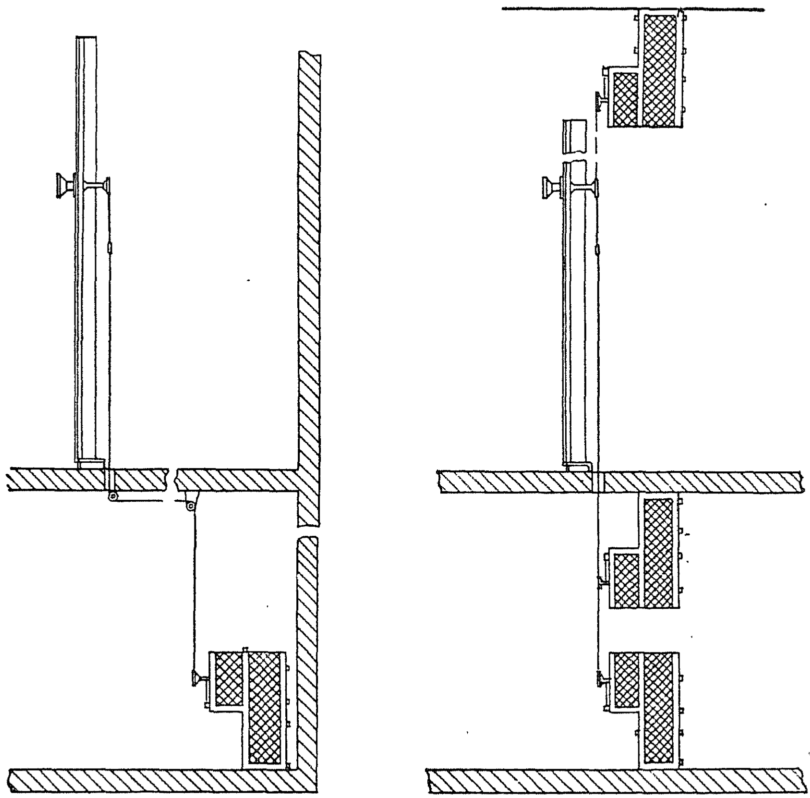


Fig. 2.—Chain Drive to Rheostats above or below Switchboard Floor

Alternatively is sometimes employed a reactive volt-ampere meter, which is really a watt meter connected to indicate the idle instead of the effective watts.

If it is intended to work a generator as a synchronous condenser, two integrating watt meters must be used if an output record is required, these instruments having restraining pawls, so that one integrates generated power, and the other power taken when motoring.

It is desirable to synchronize on the generating voltage side of a system, and, in fact, to connect here any other instruments having voltage coils, in order to save the expense and the added risk attendant upon using high-voltage potential transformers.

Where the generating station is part of a large power system, it is not always possible to avoid synchronizing on the high-voltage side. Where this is the case care must be taken to assure that the same phase relation is preserved between all points which may be connected to the synchroscope.

The most usual synchroscope is one having a rotating pointer, this having been found more easy to work with than the rotating light form. Attempts to design an automatic synchronizer have been made from time to time with indifferent success until Brown-Boveri produced their instrument, the movement of which is practically that of their well-known voltage regulator. This instrument is being employed with complete success in several of the largest Swiss power plants, including those at Olten-Gösgen and Ritom.

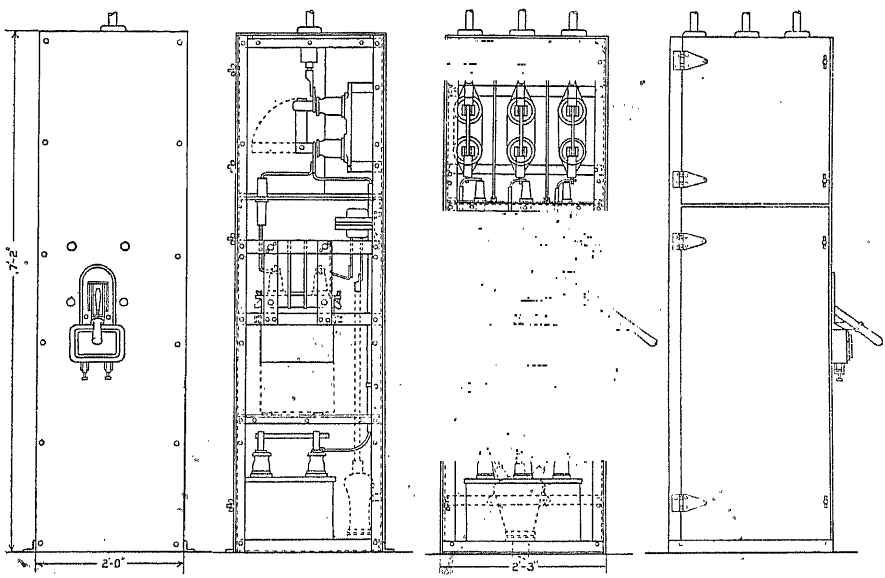


Fig. 3.—Self-contained Sheet-steel Cubicle

For small plants up to 6600 volts, where the class of operator may be only semi-skilled, the switches, bus-bars, &c., may with advantage be placed right behind the control panels, no conductor at a higher potential than 110 volts being mounted on the face of the panels. Sheet steel lends itself admirably for the construction of such switchboards. The front, sides, and back are of the same material, and either front or back hinged so as to allow of access to the switchgear within. The hinged portions should be interlocked with the oil circuit-breaker and isolating switches, so as to ensure the safety of the operator. Fig. 3 shows a typical sheet-steel panel.

Sheet-steel cubicle-type switchboards cease to be economical when the oil circuit-breakers are of such size as to require specially stiff supporting frames. In general it may be taken that the limit of application is reached with switches of 50,000 k.v.a. breaking capacity, 1000 amp. normal current, or 6600 volts working pressure. Beyond these limits sheet-steel cubicle

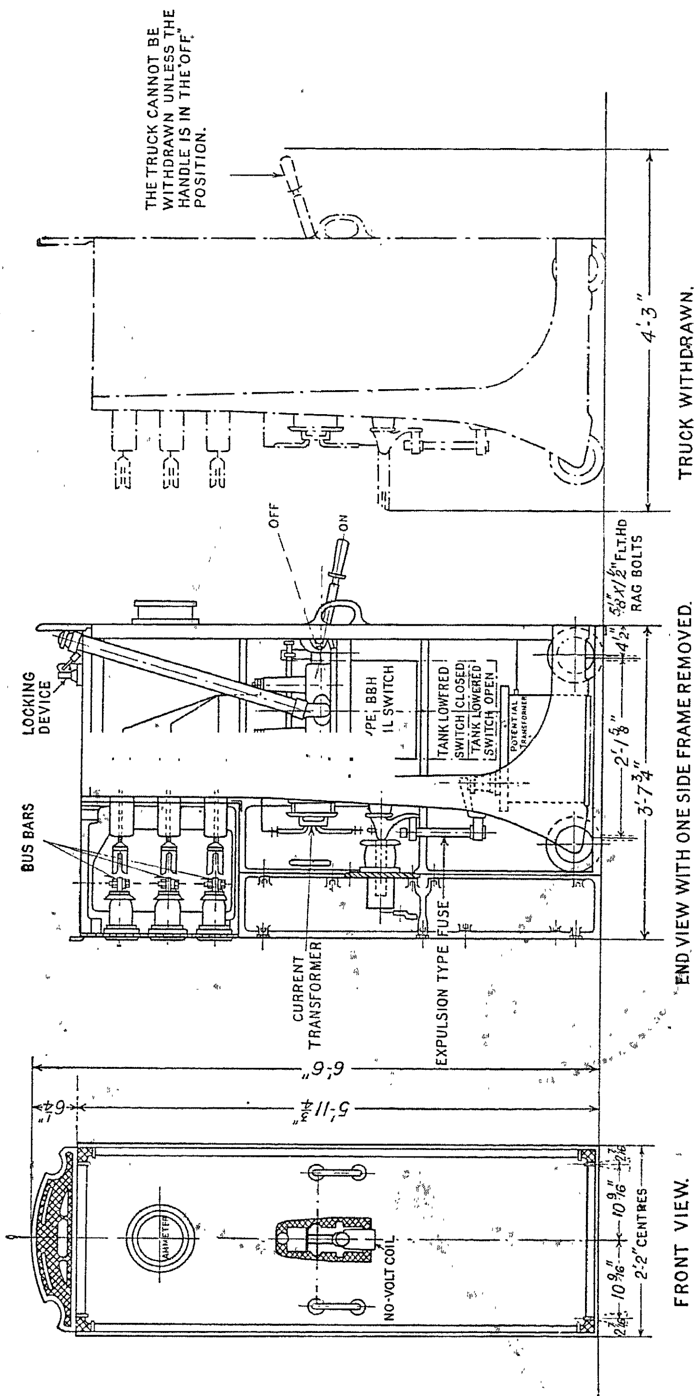


Fig. 4.—Truck-type Switch Cubicle

switchboards may be regarded as non-standard, although often entirely justifiable by reason of special circumstances.

An increasingly popular form of ironclad cubicle is that known as the truck type, and illustrated in fig. 4. In this construction the bus-bars are housed in a stationary structure, in the bottom of which is also the cable dividing box. On a movable framework is carried the oil circuit-breaker

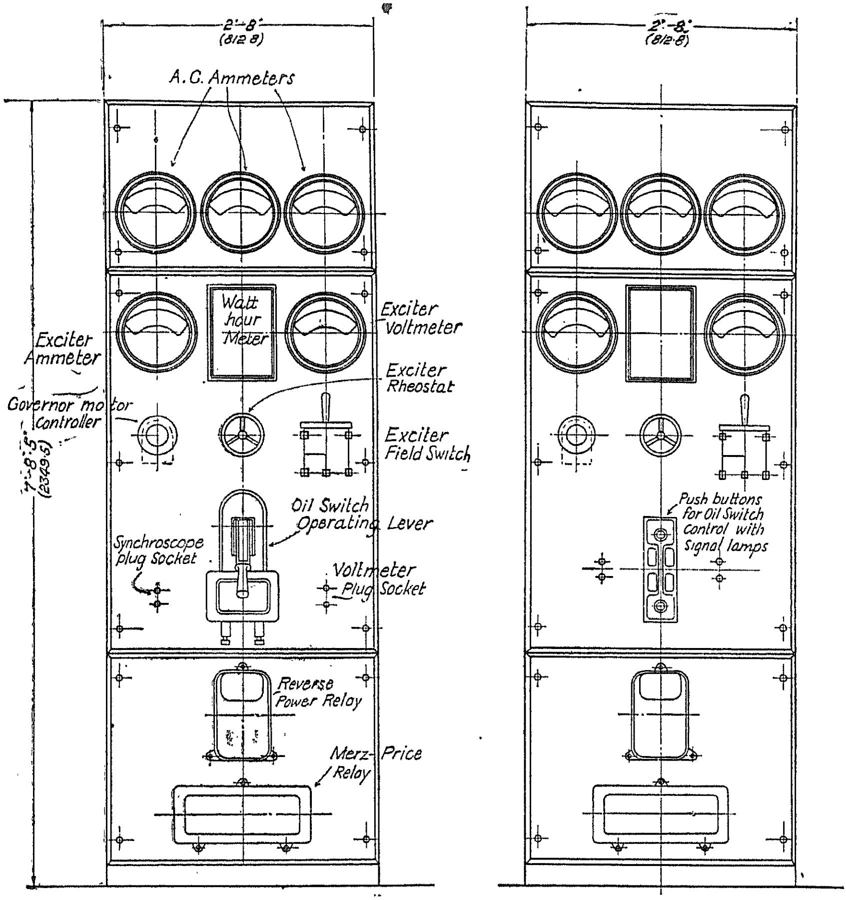


Fig. 5.—Typical Generator Panels

and instrument transformers. Connections from this apparatus terminate in a set of male contacts carried on the back of the frame, and these connect with corresponding contacts which are carried on the bus-bars and cable ends. The movable frame has a sheet-steel front panel, bearing the indicating instruments and oil circuit-breaker operating handle.

When it is desired to inspect the apparatus the whole framework can be withdrawn, enabling the equipment to be reached in perfect safety. Interlocks are provided to prevent withdrawal or replacement of the truck unless the oil circuit-breaker is open.

Equipment of this type takes up little room, as no special provision has to be made for working space. The truck can be bodily moved to any place convenient should it be necessary to carry out extensive work on the apparatus.

Beyond the limits of sheet-steel cubicle construction the switchgear will be separated from the control switchboard. It will be convenient to consider independently the forms taken by the control switchboards, and later the arrangement of the switchgear itself, since these may be employed in various combinations to suit the requirements of each installation.

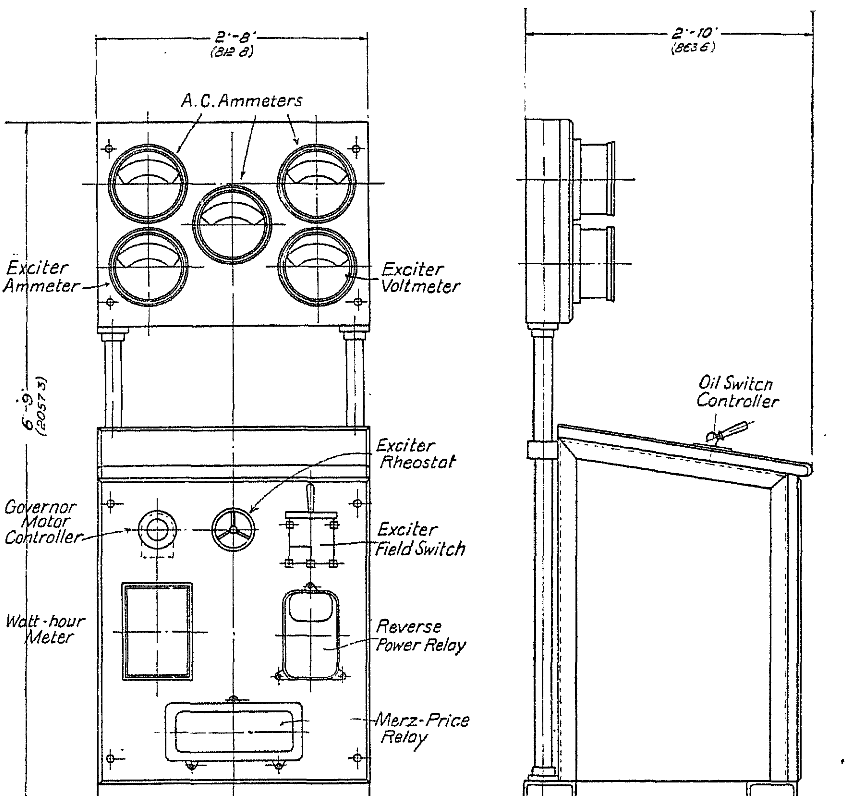


Fig. 6.—Typical Generator Desk

Panel-type control boards are generally employed where low first cost is of great importance, and where the number of instruments, relays, &c., is not so large as to make the complete switchboard unwieldy. To be easily read the highest instruments should not be more than 6 ft. from centre to floor. The indicating instruments used in this country are generally about 9 in. base diameter (in America, 7 in.), so that two may be mounted side by side on a panel 20 in. wide, or three on a 32-in. panel. Wider than this it is not desirable to go.

In the illustration (fig. 5) are shown two typical generator control panels, the one for use with mechanically operated oil switches, and the other for

an electrically controlled equipment. The generator equipment has been selected for sake of example, since this usually has more items of apparatus than are needed for any other circuit. It will be noted that these panels carry main ammeters, watt-hour meter, exciter ammeter and volt meter, exciter rheostat handwheel, field switch, plugs for the machine volt meter and synchroscope, governor control switch, oil circuit-breaker operating

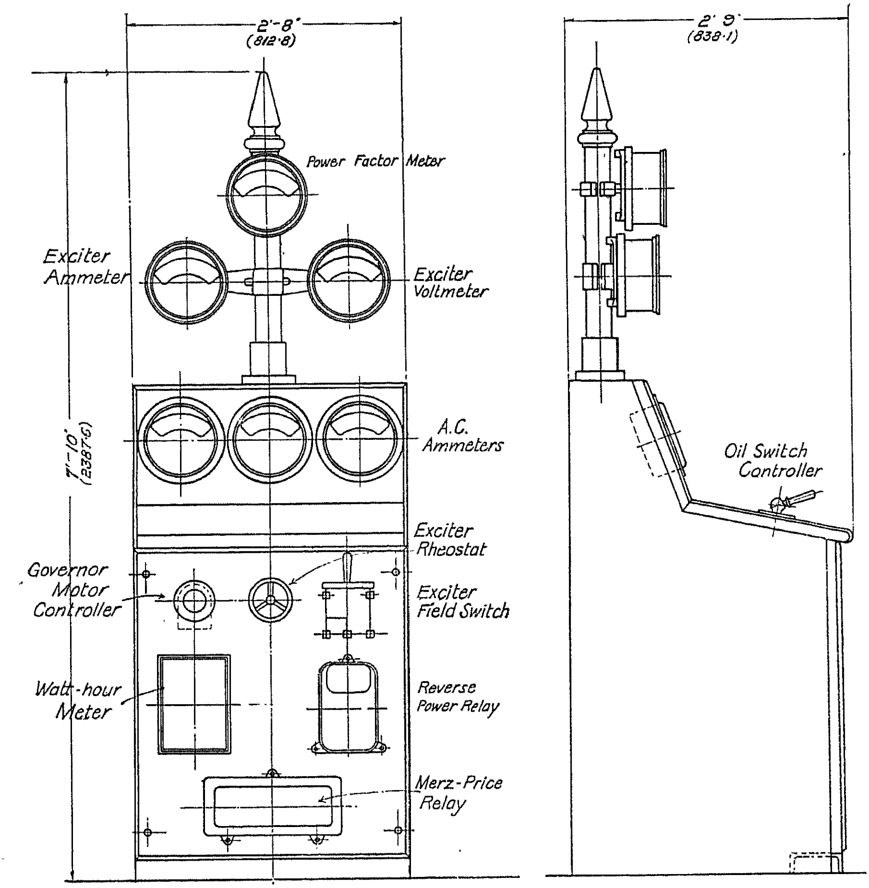


Fig. 7.—Typical Generator Desk (Continental style)

device, and balanced current relay. This is the minimum equipment for a generator, for which might also be required an individual volt meter for each generator panel, an integrating watt meter (or possibly two), signal lamps, testing terminals, a reverse power relay, a high-setting overload relay, or an exciter field switch.

If the control board is within sight of the generator room, it must of necessity be so located that the operator stands between the two, and his back will be turned to the machines whenever he is observing his instruments. To avoid this difficulty, desk-type boards (figs. 6 and 7) were introduced,

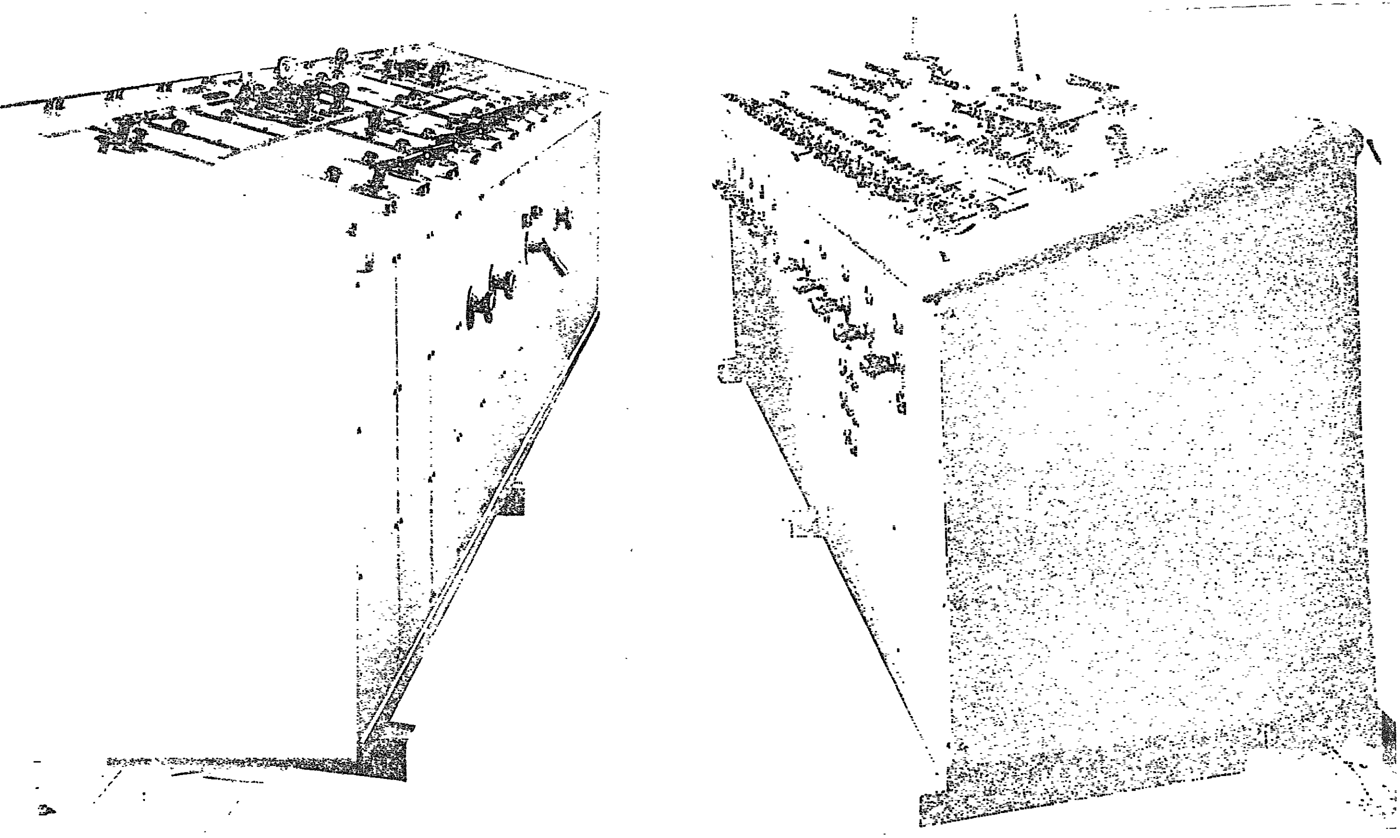


Fig. 8.—City of Winnipeg: Control Desk bearing Dummy Diagram

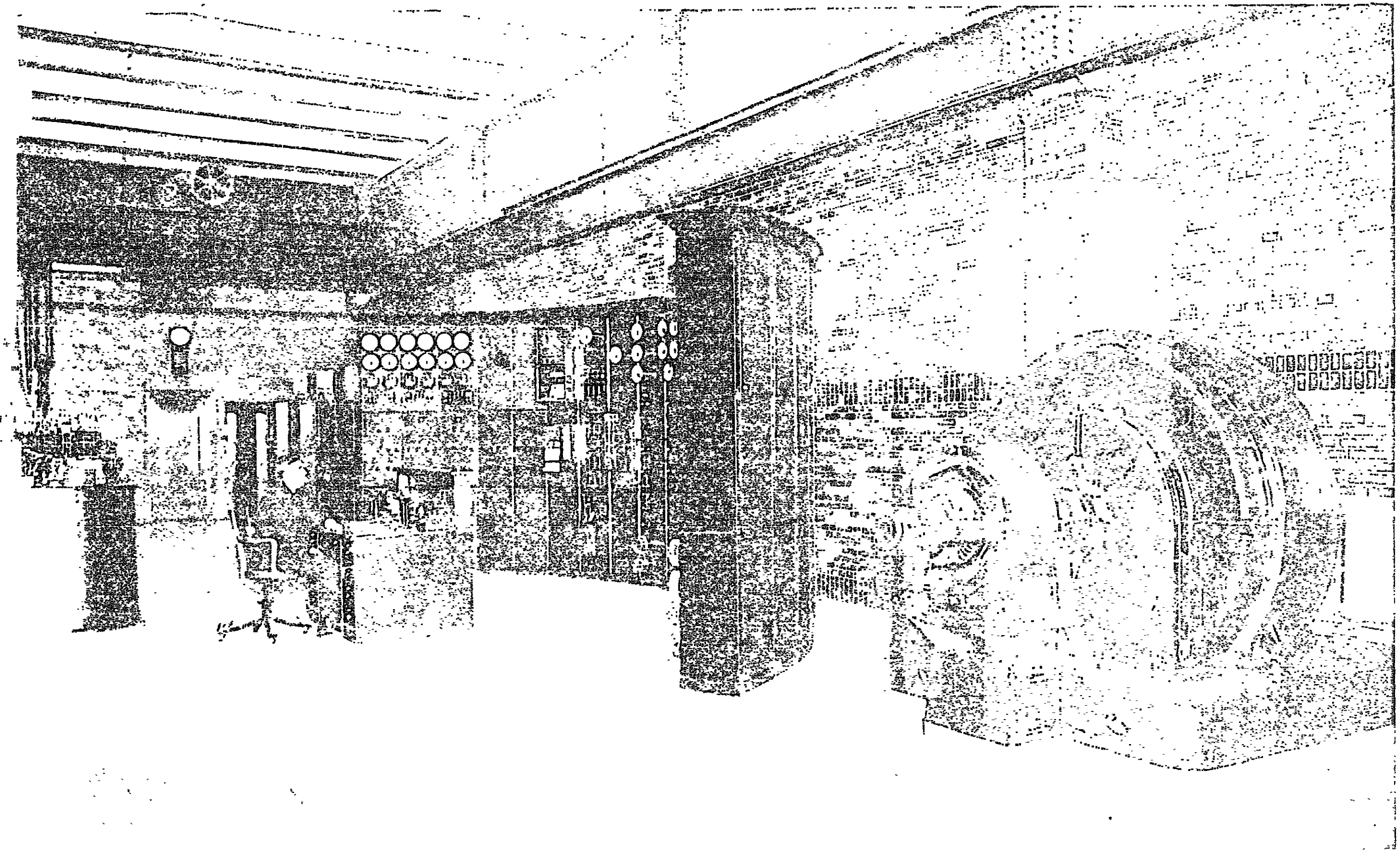


Fig. 9.—Control Switchboard in Semicircle around Operator's Desk

as with these it is possible for the operator to see the generator room either over or through the desk structure. The upper slab, on which the indicating instruments are carried, must clearly be kept within the same height limits as in the case of a panel-type board. It follows that the available space on a desk board is, if anything, less than on a panel, since clearance must be provided between instrument terminals which come close into the angle between vertical and horizontal slabs. As a rule desks are not used with mechanically operated circuit-breakers, as the levers would come inconveniently low.

A feature common on both American and Continental desk-type control switchboards is the dummy diagram. In fig. 8 is shown the desk board in the City of Winnipeg power station, on the face of which will be seen the dummy diagram. A single-line diagram of the system is reproduced with strips of metal on the face of the desk, conventional signs being used to indicate generators and transformers. Either a small electro-magnetic device or a signal lamp placed in the run of the diagram is used to indicate whether each oil circuit-breaker is open or closed. In a few installations, three such pilot lamps are used for each circuit-breaker, these indicating, respectively, breaker closed, breaker opened by hand, and breaker opened by operation of relay.

The position of isolating and selector switches is usually indicated by small hinged links in the dummy diagram, these being turned by hand whenever any change is made. Since, to be of any use, the diagram indications must be absolutely above suspicion, the author is strongly in favour of signal lamps for these switches also. It is true that this practically necessitates mechanically coupled and operated switches to move the necessary auxiliary switch for the signals, but if operating conditions make these inadvisable, it is better to dispense with the dummy diagram.

There is no doubt that with a large switchboard, or one in the main connections of which there is any approach to complication, the dummy diagram is of great value to the operator, since he can actually see the effect of a proposed operation, and is not obliged to rely on his memory of the system.

With the big generating stations now in vogue there is a tendency for the control board to be too long for convenient and quick operation. In such cases, separate control and instrument panels are advisable. The dummy diagram, with all control switches, rheostat handwheel, synchronizing gear, or other apparatus essential for actual control, is mounted on a desk, the indicating and recording instruments, with all relays, being carried on panel boards at the rear. By putting the equipment in two rows the over-all length is approximately halved. The relative disposition of these two boards is to some extent flexible. In some cases the desk is so placed as to command a view of the generator floor, with the panels facing the desk, so that the operator has to turn round to see all his meters except the synchronizing apparatus.

In those stations where the switch house is segregated, the desk may well be in the middle of the control-room, and have only the generator control

apparatus upon it. Panel-type boards, arranged in a semicircle facing the operator, carry all generator instruments, as well as the complete feeder control equipments and their dummy diagram. Such an arrangement is shown in fig. 9.

Another widely-used method is to have all indicating instruments on a slab above and forming part of the control desk, with a panel at the rear to carry relays, and integrating and recording instruments, which do not require to be inspected at frequent intervals. (See fig. 10.)

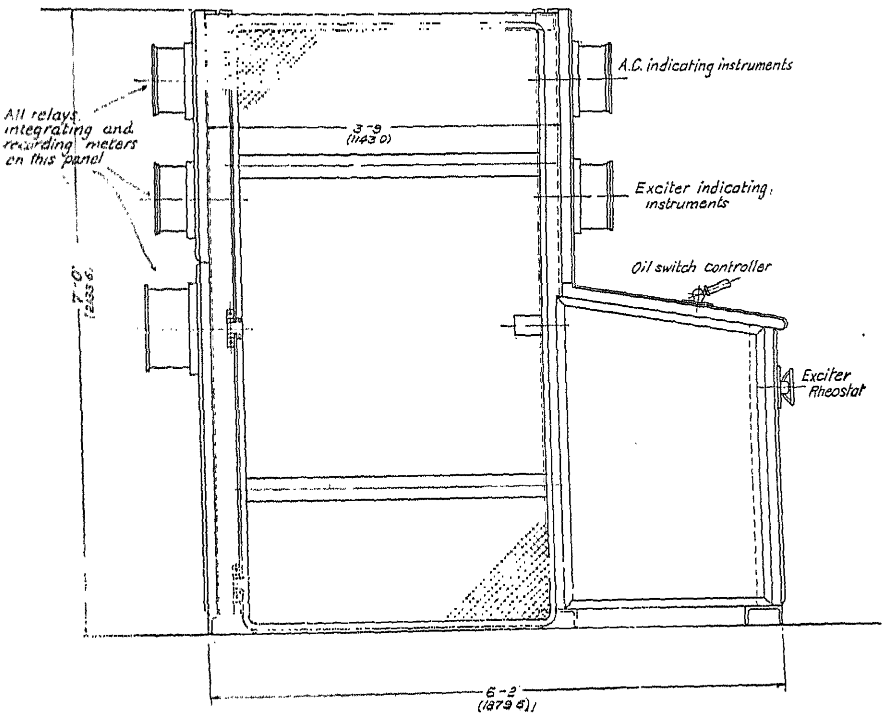


Fig. 10.—Desk with Separate Relay Panels

The last scheme is good in that it lends itself to visible wiring. It is extremely difficult and equally important so to arrange the small wiring behind a switchboard as to be easily traced. Circuit-breaker control wires should be separated from selector switch pilot lamp circuits, and leads from potential transformers should be readily distinguishable from the relay and the indicating instrument current transformer connections.

An excellent method applied by some Continental makers to panel-type control boards is shown in *E. T. Z.*, 29th Jan., 1920, p. 86. Between each pair of panels, at the rear, is mounted at right angles a supplementary panel, usually of asbestos slate or some similar material, and on this are carried the main control wires in their proper groups. Not only does this arrangement tend to prevent trouble and to facilitate repair, but it renders it much easier

to make periodical checks on all instruments and relays. A considerable sum of money may be well invested if clearly laid out wiring is obtained.

In the same way the conductors from cubicle to switchboard should be properly grouped. They are commonly run in buried conduits, or as multi-cored cables drawn through ducts. Whenever possible, however, such cables or conduits should be cleated on the face of walls or ceilings, so as to secure maximum accessibility.

2. Cubicle Structures.—In stations where sheet-steel cubicle construction is not practicable, the switchgear at generating voltage, say up to 13,500 volts, is enclosed in cubicles built of concrete, or constructed with flat slabs of asbestos wood or of plaster. In British and general European practice, similar cubicles are in fact used up to 35,000 volts, but American engineers favour open construction for these higher pressures.

The material to be used in making cubicles is largely dictated by local conditions and the class of labour available. Concrete work is almost invariably used in Great Britain and also in America. It is unusual to use steel reinforcing rods, even when moulding on site, although excellent structures are made with flat concrete slabs, supported on angle-iron framework.

No matter what material is employed, sound practice demands that the cubicle material be considered as a conductor at earth potential, and full clearance maintained between it and all live metal. Metal bases, such as the supports for isolating switches, bus-bar insulators, or oil switch mechanisms must nevertheless be properly connected to an earth wire which takes in the general steelwork of the station building.

Considering first those structures up to 13,500 volts, it will be found that British and American designers endeavour to economize in space as far as is reasonably possible, while Continental designers use all the space they can get. In an article in the *BEAMA Journal*, Oct., 1920, attention was drawn to this, and the case illustrated in figs. 11 and 12 was cited. The two equipments shown are the proposals made by a Continental firm and by a British concern in respect of the same project. This may perhaps be an unusually exaggerated case, but a study of numerous installations shows a very distinct space advantage in favour of British lay-outs.

In designing a cubicle structure, fire risk and danger from short-circuit must be kept constantly in mind, and these two are closely allied. The liberal spacings adopted by Continental designers are dictated by these considerations, and by their experience showing that their oil circuit-breakers not infrequently explode.

The question of circuit-breaker selection has been dealt with in a previous chapter. That section of the structure in which the circuit-breaker is housed should be properly separated from the rest of the apparatus. Means should be provided to conduct the gases from the switch top outside the cubicle and clear of all live metal. Within this cubicle no bare conductor should be exposed. The leads should be taken through the cubicle walls in tightly fitting insulating bushings.

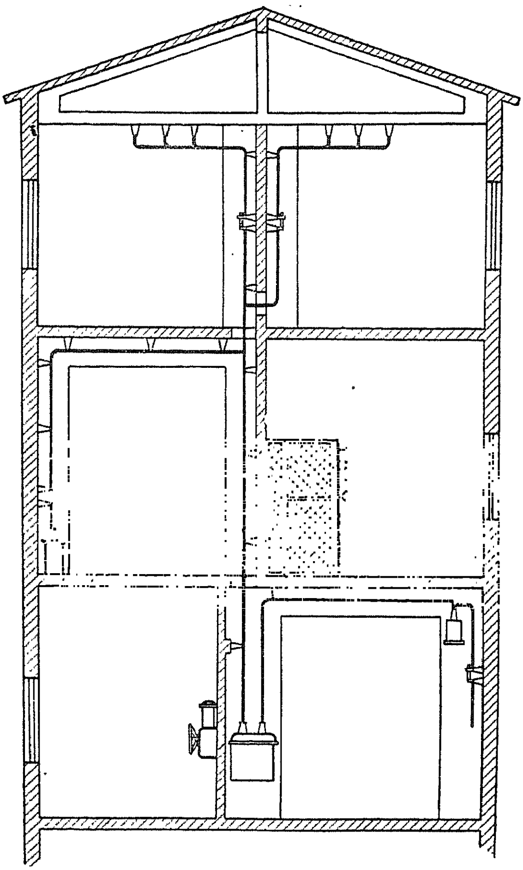


Fig. 11.—Section through Switchgear by one of the large Continental Manufacturers, for control of an 11,000-volt Transformer Sub-station

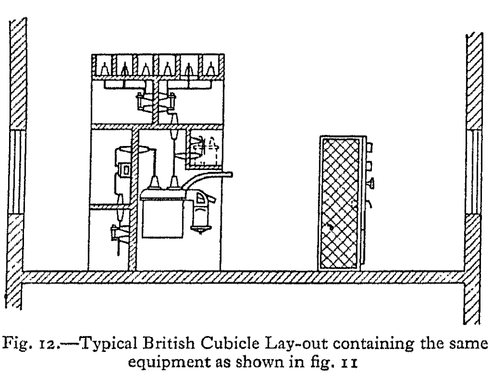


Fig. 12.—Typical British Cubicle Lay-out containing the same equipment as shown in fig. 11

There is no need to take the gas relief pipes into a common main, exhausting outside the building. Unless an exhaust fan is fitted and kept constantly at work, such an arrangement will probably defeat itself, since there will be no current, and gas will collect along the whole main pipe, remaining constantly in the switch top. If the vent pipe is kept short and free from bends, the gases will be properly dissipated in the air, and cleared away in the course of the ordinary ventilation of the switchroom.

The oil switch cubicle may be built with a sill in front, so as to catch any oil which may leak, or fall from a burst switch. If this is done, it must be of sufficient height to hold the full contents of the tanks. It is also necessary to complete such an arrangement by having solid, closely-fitting doors, which have a lip at the bottom, overhanging the sill, to ensure that thrown oil is kept within bounds. In some instances all these compartments are drained into a common sump outside the power house, so that in the event of accident no oil will be present to increase the fire risk. In general British practice these features are left out, and it must be admitted that damage traceable to their omission does not occur, although considerable care is devoted to this detail on the Continent.

Apart from the oil circuit-breaker compartment, the main function of

the cubicle is to form at once a support for the apparatus and a barrier to prevent accidental contact with, or short-circuits between, live conductors. As previously stated, all cubicle masonry must be treated as though it were earthed metal, since all such materials are hygroscopic. Clearances from conductor to cubicle work must be the same as between conductors in opposite phases. The following should be regarded as minimum clearances:

650 volts	....	½ in.
2,200 ,,	....	1 ,,
3,300 ,,	....	1¼ ,,
6,600 ,,	....	2 ,,
11,000 ,,	....	3 ,,
13,000 ,,	....	3½ ,,

The question of safety to the operator is one which has received much attention of recent years. There is a growing inclination to interlock cell doors with the switch mechanism, so that a cell cannot be opened up unless the circuit is dead. This is a feature which must either be done thoroughly or not done at all. For instance, where the leads above an oil switch are insulated, primarily to prevent gases from starting an arc, the insulation should be adequate for the voltage, so that a man can safely grasp it with the conductor alive.

Similarly, it is unsafe elaborately to interlock all doors with the oil switch

Circuit-breaker.	6600 Volts.						11,000 Volts.					
	A.		B.		C.		A.		B.		C.	
	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.
Type BH												
Single bus, horizontal	5	0	8	9	3	0	6	0	10	3	3	3
,, vertical	5	0	10	9	3	0	5	6	12	6	3	3
Double bus, horizontal	5	8	10	0	3	0	7	6	11	0	3	3
,, vertical	5	6	12	0	3	0	7	3	14	6	3	3
Type HF1												
Single bus, horizontal	6	9	9	9	5	4	7	9	10	6	5	4
,, vertical	6	9	12	6	5	4	6	10	13	6	5	4
Double bus, horizontal	6	9	12	10	5	4	7	2	13	7	5	4
,, vertical	6	9	14	6	5	4	6	9	16	3	5	4
Type HF5												
Single bus, horizontal	7	3	9	10	6	6	7	8	10	9	6	6
,, vertical	7	0	12	9	6	6	7	3	13	10	6	6
Double bus, horizontal	7	0	13	3	6	6	7	3	14	0	6	6
,, vertical	7	0	15	0	6	6	7	3	16	8	6	6
Type O-1												
Single bus, horizontal	7	0	10	10	7	0	7	3	10	10	7	0
,, vertical	7	0	12	9	7	0	7	3	13	0	7	0
Double bus, horizontal	7	0	14	6	7	0	7	3	15	0	7	0
,, vertical	7	0	16	0	7	0	7	3	20	0	7	0

mechanism, if it is only possible to draw the isolating switches after the doors are open, since a false sense of security is given which may cause a man absently to touch a still live conductor.

Considerable elaboration is necessary to effect complete interlocking on a cubicle, since one contact of isolating or selector switches is always liable

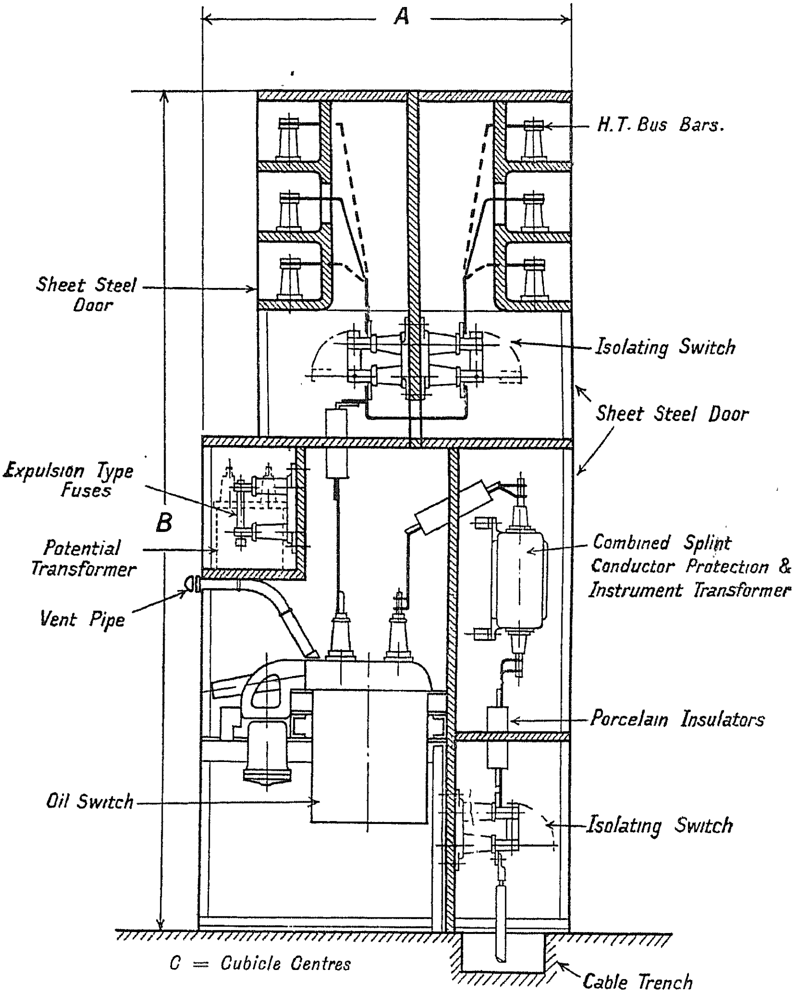


Fig. 13.—Typical Cubicle with Top-connected Switches and Double Bus-bars

to be alive, although the blade may be in the open position. This contact should therefore be shrouded so as to make it inaccessible at all times, and the remaining portions of the equipment should be guarded until both oil switch and isolating switch have been opened from without the cubicle.

In the majority of central stations it is believed to be better merely to have all cubicles enclosed with screen work to prevent accidental contact

in passing, these screens being fastened with an ordinary lock. Only skilled operators will require to have access to the apparatus when a cubicle is opened.

It should be made clear that the foregoing remarks on the arrangement of switchgear in cubicles apply only to cubicle-type apparatus. They have

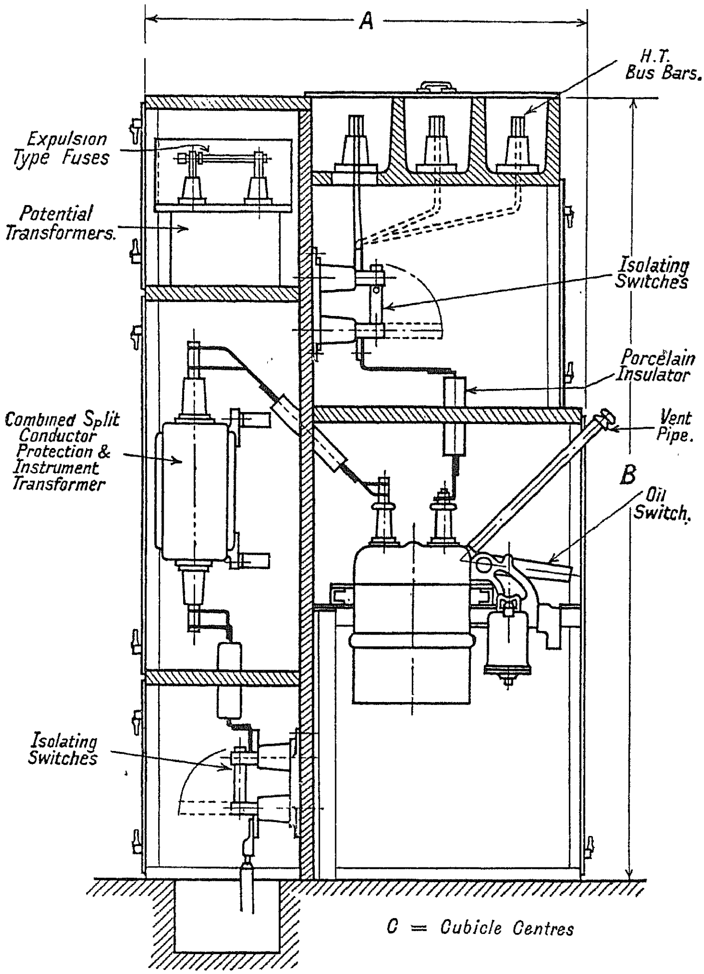


Fig. 14—Typical Cubicle with Single Bus-bars

little or no bearing on the ironclad switchgear made by many firms for industrial service, and of which Messrs. Reyrolle's manufactures are typical in the wider field of central station work.

To enable preliminary estimates of space to be made, a table (p. 209) is presented referring to structures such as are shown in figs. 13 and 14, and covering installations requiring circuit-breakers with rupturing capacities from 50,000 to 500,000 k.v.a. It is neither necessary nor possible to give

any but over-all dimensions which tend rather on the high side. Dimension " A " is given for electrically operated switches. When mechanical operation is employed, " A " is reduced by reason of the omission of the solenoid.

Although the cubicle arrangements illustrated are based on the apparatus of the Metropolitan-Vickers Electrical Company, it will be found generally that other makers require approximately the same space.

The illustrations show cubicles which are reasonably compact when arranged with double vertical and single horizontal bus-bars respectively. When using large-capacity switches, however, a single floor structure is not always quite practicable, since the

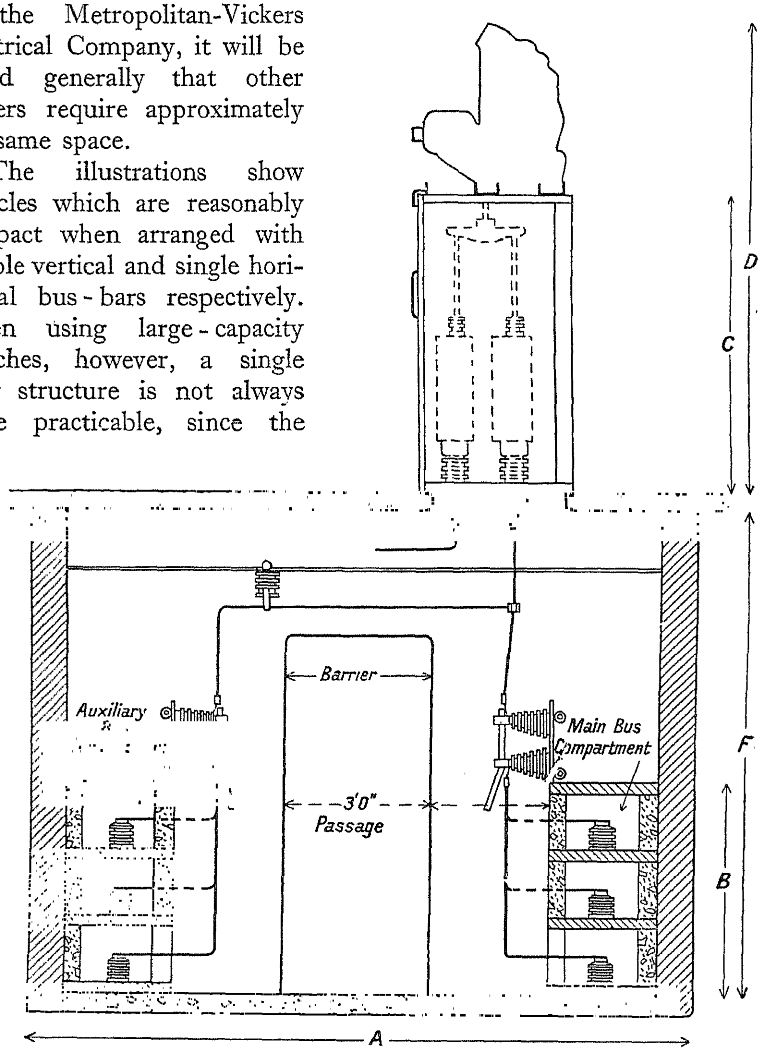


Fig. 15—Single Cubicle with Bottom-connected Switches

isolating switches are necessarily high up. In such cases the bus-bars and isolating switches may advantageously be located on a floor above that on which the oil circuit-breakers and other apparatus are carried.

The dimensions given will cover equipments for currents up to about 600 amp. Where heavier currents are to be handled, the dimensions will

be somewhat larger. Where neither potential transformer nor a set of isolating switches on the cable side are required, the height can often be reduced. The cubicle centres " C " will hold good for split conductor equipments, except in the smallest size, where 12 in. extra should be allowed for the accommodation side by side of six isolating switches.

The outstanding exception to these typical cubicle arrangements is in the case of certain switches built by the British Thomson-Houston and General Electric Companies, and known as their " pot " type. These switches have two separate tanks per pole, which may be placed either side by side or one behind the other. They are most conveniently made bottom connected (although they can be made rear connected), so that with them the general arrangement of structure is inverted, with the bus-bars below the oil switch.

In fig. 15 is shown a typical double bus-bar structure for the " pot " oil switch, from which comparison can readily be made with the corresponding conventional cubicle.

The following table gives the approximate dimensions for such an arrangement. The height shown between the two floors is dictated by the height of the doorway in the lower voltage arrangements. This has been taken as 6 ft. Standard British practice would demand greater space, since with the lay-out shown the Home Office required a clear gangway 4 ft. 6 in. wide, with a headroom of 8 ft. to live metal.

Circuit-breaker.	A.		B.		C.		D.		E.		F.	
Type H3.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.	ft.	in.
6,600 volts ..	9	0	3	4	5	2	8	1	4	6	8	0
15,000 volts ..	9	6	3	8	5	2	8	1	4	6	8	4
22,000 volts ..	12	0	5	8	6	4	10	0	7	1	11	0
Type H6.												
6,600 volts ..	9	0	3	4	5	8	8	8	5	1	8	0
15,000 volts ..	9	6	3	8	5	8	8	8	5	1	8	4
22,000 volts ..	12	0	5	8	6	8	10	4	8	8	11	0
Type H9.												
6,600 volts ..	9	0	3	4	6	6	9	6	7	0	8	0
15,000 volts ..	9	6	3	8	6	6	9	6	7	0	8	4
22,000 volts ..	12	0	5	8	7	6	11	2	10	7	11	0

The dimensions given are those of the cubicle itself. As a rule, in any complete structure the height and the depth from front to back are uniform and are dictated by the dimensions of the largest unit. The British Home Office Regulations demand a clear passage way in front of all cubicles containing conductors at high potential. The minimum dimensions for 650 volts or less are 3 ft. wide by 7 ft. high. Over 650 volts a minimum headroom of 8 ft. is required, with a width of 3 ft. 6 in. if there are live conductors on one side only, or 4 ft. 6 in. if there are conductors on both sides of the passage. In large plants it will usually pay to increase this dimension on

the oil-switch side, in order to facilitate erection and possible repair. American practice usually tolerates much smaller passage ways than are used in this country.

Circuit-breakers of capacity up to about 150,000 k.v.a. and currents of 1000 to 1500 amp. can usually be adapted for hand operation through a mechanical system of levers and links. Beyond this, electrical operation is desirable, since a heavy switch cannot be closed quickly. This is specially

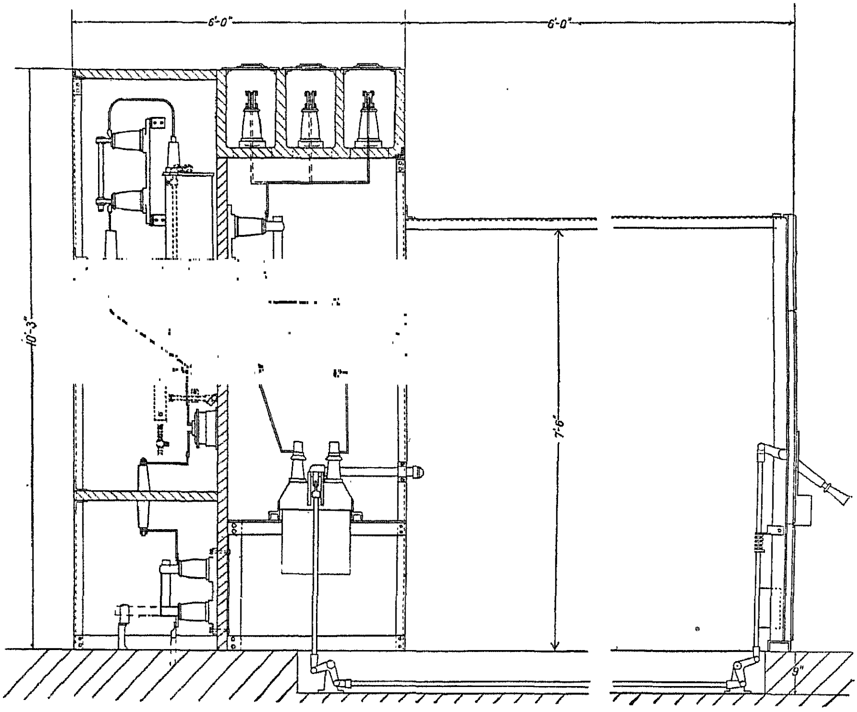


Fig. 16.—Typical Remote Mechanical Control from Switchboard

important on those circuits which have to be closed when synchronizing machines.

A typical arrangement of remote mechanical control is shown in fig. 16. As a rule the trip catch for the circuit-breaker is on the hand lever at the switchboard, and care must be exercised to ensure that the link system is properly balanced so that it does not retard the opening movement, but if anything assists it. When closing the circuit-breaker, all links, which are usually lengths of standard ½-in. gas pipe, must be in tension. Operation becomes too stiff if more than three bell cranks or 20 ft. of rod are employed, and if the circuit-breaker be offset in relation to the closing lever by more than 15°, it is preferable to use a way shaft in the drive, and thus avoid the necessity for big clearances around the hinge pins.

An increasingly important phase in the design of switch structures in

large plants is the adequate bracing of conductors. In the section on the use of reactances, brief reference was made to the stresses which are set up under short-circuit current conditions. Where the three conductors of a three-phase circuit lie in the same plane (which is usually the case), the repulsive force is given by the formula:

$$F = \frac{8{\cdot}08 \times I^2 \times 10^{-7}}{d},$$

where F = maximum repulsion in pounds per foot run;
d = distance in inches between centres of conductors;
I = r.m.s. value of current in each conductor.

As d will customarily be around 12 in. on structures such as are now under consideration, very high repulsive forces may be encountered.

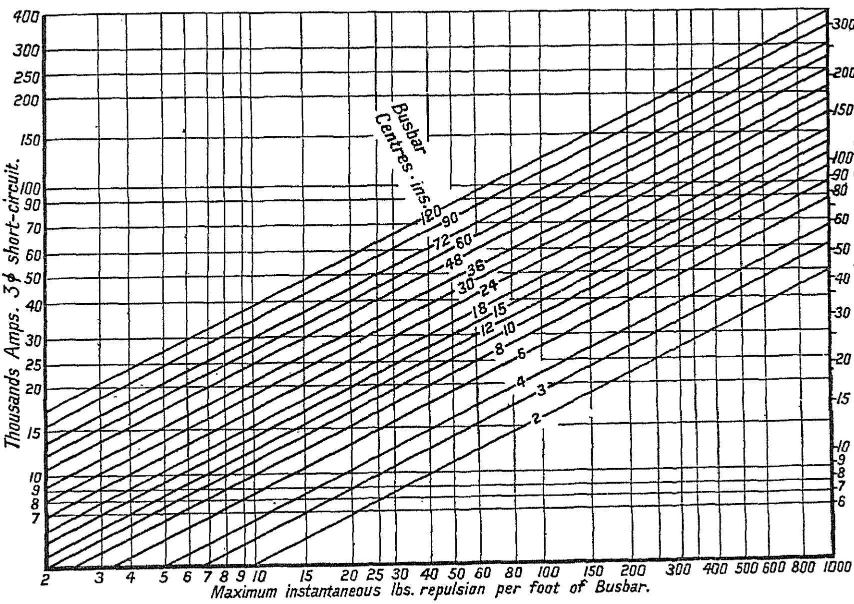


Fig. 17.—Diagram showing the Repulsive Forces with Conductors in the same Plane*

The curves in fig. 17 are based on the formula given above. In using these, care must be taken to employ the instantaneous short-circuit current value, and not the values used in selecting oil circuit-breakers, which are, of course, smaller.

On small structures the bus-bars and other conductors are supported solely on the studs of the oil switches, isolating switches, and other apparatus. Such will invariably be found insufficient if the plant be of any considerable size, especially since the porcelain insulators of the switches, &c., cannot

* See "Repulsion between Bus-bars", C. R. Riker and S. R. Leonard, *Electric Journal*, December, 1917.

be used to best mechanical advantage. It must be borne in mind that although good wet-process porcelain will show an ultimate value of 15,000 to 18,000 lb. per square inch in compression, it will only give about 1200 to 1600 lb. per square inch in tension.

The compression type of bus-bar support has been developed for use where the short-circuits are exceptional. As will be seen from the illustration, fig. 18, two porcelain insulators with the conductor between them are used, these having their axes lying in the same plane as the three conductors. With the clamps screwed up tight, any repulsive stresses will necessarily come upon one insulator in compression.

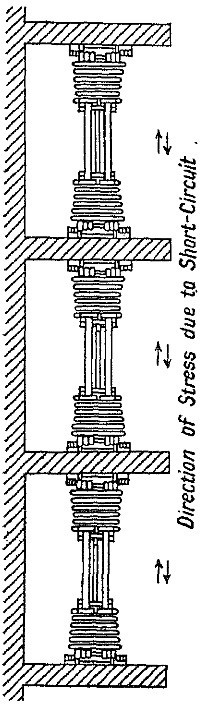


Fig. 18—Compression Bus-bar Support

Even where the stresses are insufficient to necessitate the use of compression insulators, it is advisable to calculate the deflections between supports on small conductors, to ensure that these cannot come within the limit clearances from earth, under maximum short-circuit conditions. Clearly it will be best from this angle if conductors are arranged edge to edge, so as to get maximum stiffness in the plane of the repulsive forces.

It is also necessary to take special precautions with small connections, such as the leads to potential transformers, on large systems. A short-circuit across the terminals of such a transformer may easily be of sufficient magnitude to melt entirely the conductors between it and the bus-bars, and, moreover, would be too great to be successfully broken by any known type of fuse.

To illustrate the point the curves in fig. 19 are given. These have been calculated for the case of a steam turbine station in which the generators have an initial short-circuit current of ten times normal, dying down to three times normal in two seconds. Reference may be made to the original article, "Small Conductors on Bus-bars of Large Systems", W. A. Coates, *Metropolitan-Vickers Gazette*, June, 1920.

A protective resistance should be used in series with potential transformers, so as to limit the short-circuit current to a value which can be safely handled under all possible conditions. The resistance should be divided and mounted half on each side of the potential transformer, so as to ensure the presence of limiting resistance, no matter where the trouble may be.

With very big, low-voltage generating stations, the consideration of maximum temperature under fault conditions may affect the size of copper used for connecting up small feeder circuits. Operating rules generally demand that in the event of a circuit-breaker tripping out, the attendant shall wait from $\frac{1}{2}$ to 2 minutes and then reclose it. Only after a second automatic operation is the circuit left open. The following minimum areas of copper conductor are suggested as desirable.

Aggregate instantaneous short-circuit possibility at point of installation.	Three-phase Volts.	Minimum Area, square inches.
1,000,000 k.v.a. ..	6,600/11,000	0·375
	20,000/25,000	0·25
	35,000	0·125
500,000 k.v.a. ..	3,300	0·375
	6,600	0·25
	11,000/25,000	0·125
250,000 k.v.a. ..	3,300	0·25
	6,600/11,000	0·125

Apart from this consideration, the area of conductors should be based on temperature rise. For many years a rule-of-thumb standard was employed

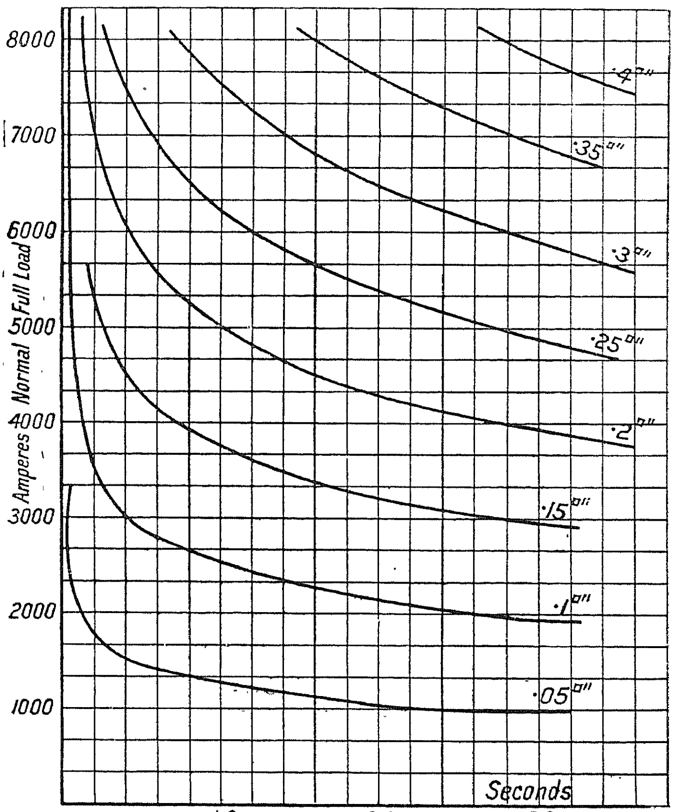


Fig. 19.—Diagram showing Time for a Conductor to reach 500° C. on Generator Short-circuit

by which the area was based on 1000 amp. per square inch, irrespective of the shape, total size, or location of the conductors. British standard practice

demands that no part of the bus-bar system or of the connections, excepting resistance elements such as meter shunts, shall have a temperature rise exceeding 30° C. A hottest-point margin of 5° C. is permitted above this average figure. In no case may the density exceed 1000 amp. per square inch of copper.

To keep within the limit of 30° C. it is sound practice to design for a calculated rise of 20° C., since it is impossible to arrange all parts of the main connections so as to secure perfect ventilation. Bolted or clamped

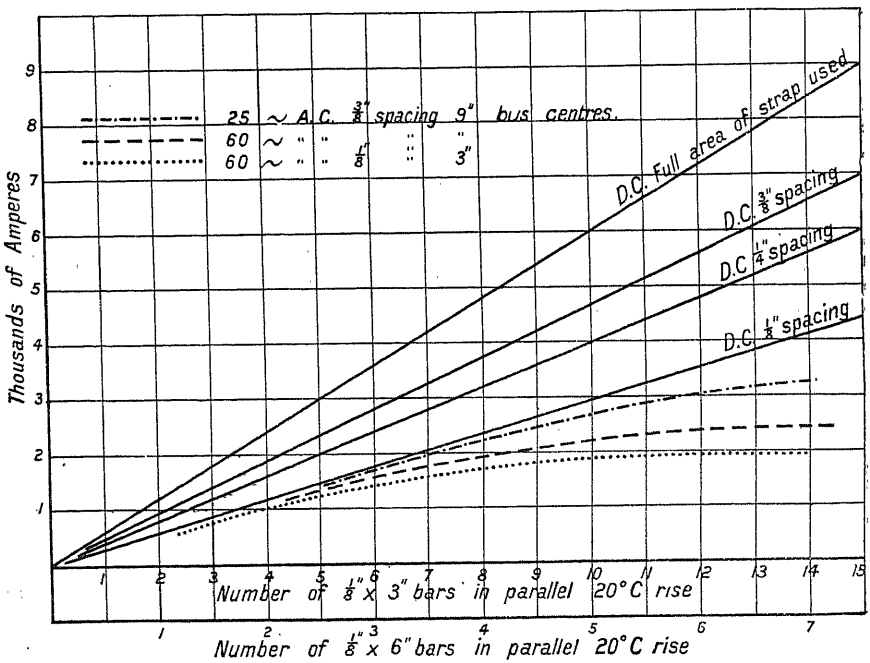


Fig. 20.—Carrying Capacity of Copper Bars at various Spacings

connections also are a frequent source of local heating, for which allowance has to be made.

With a single bar on edge, all faces may be considered as fully employed for radiation. The inside surfaces of bars in parallel are only partially effective, since they tend to form hot-air pockets. Experimental results show that with two bars in parallel, each having a surface A, the total effective surface of the pair:

spaced $\frac{1}{8}$ in. apart = 1·2A,
" $\frac{1}{4}$ " " = 1·3A,
" $\frac{3}{8}$ in. " = 1·6A.

The curves given in fig. 20 may be used as a basis for design to temperature rise. It will be observed that single $\frac{1}{8}$-in.-thick bars on D.C. could actually be worked well over 1000 amp. per square inch, and still be within

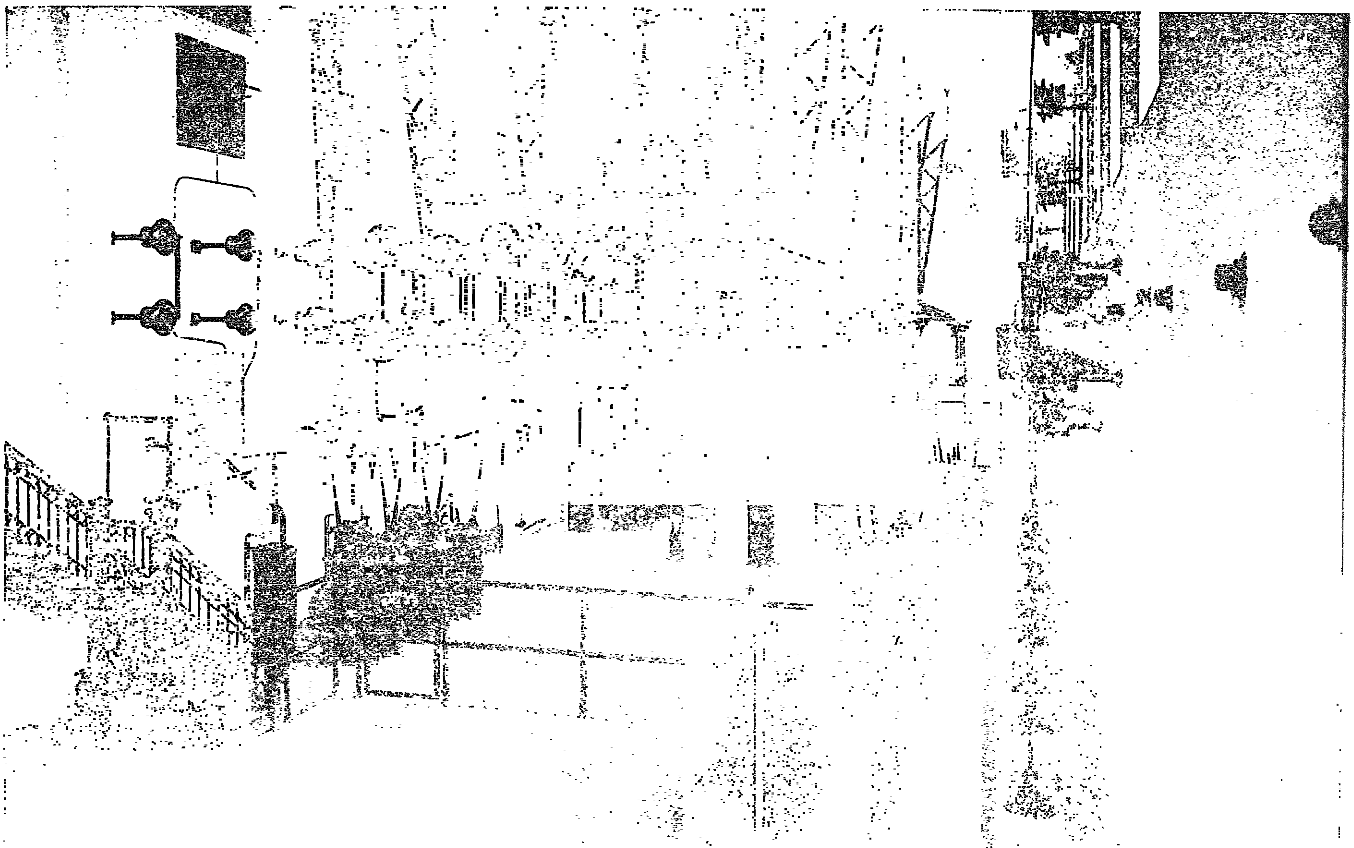


Fig. [illegible].—Winnipeg City. Interior of High Voltage Switchroom.

the 20° C. rise. If bars $\frac{1}{4}$ in. thick are used, the section is doubled, but the radiating area only slightly increased. The thinner bar is consequently to be preferred.

Attention is drawn to the reduced capacity of the conductors when on A.C. This is due to the skin effect and to mutual induction between one bar and the next. When carrying very heavy currents, as with furnace transformers, interleaving of phases must be resorted to.

3. High-voltage Arrangements.—In the previous section attention was given to the arrangement of switch apparatus in cubicles, and it was then assumed that such structures would be used for pressures not over 13,500 volts. Above this limit, it is a matter for investigation in each case to determine whether cubicle work will pay or not. In modified form cell work has been employed up to 80,000 volts or even higher, but the majority of such high-voltage switching equipments are laid out along other lines, using simple steel framework to support all apparatus. The open construction has as chief advantage a considerable saving in first cost, since the steel framework is cheaper than a complete concrete structure, and, further, the total space occupied is generally less.

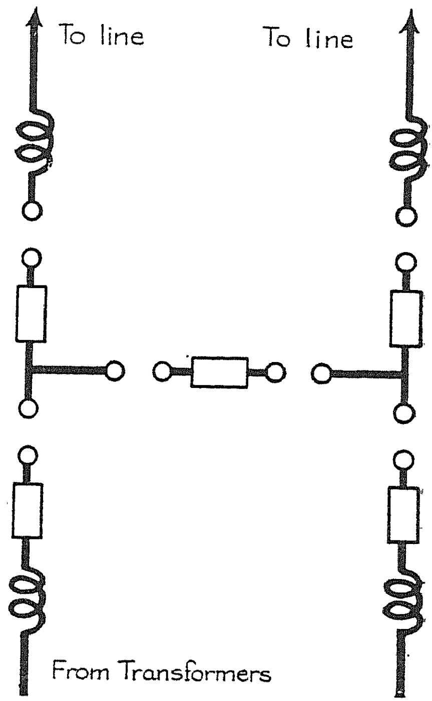


Fig. 22.—Diagram of 72,000-volt Connections shown in fig. 21

High-voltage switching arrangements are usually much simpler than those adopted for lower pressures, since all measuring devices are confined to the low-voltage side of the system. The lay-out can consequently be made diagrammatically, and with an open structure it is often claimed that an attendant is less likely to make mistakes than would be the case if each piece of equipment were concealed in a cubicle.

Open structures are almost invariably used in America, and are also used to some extent on the Continent. An excellent example of the diagrammatic lay-out of apparatus along these lines is furnished by the switchgear at the Point du Bois Station of the City of Winnipeg. This is illustrated in the photograph, fig. 21, and the corresponding diagram is given in fig. 22. From this it will be seen that the high-voltage switches provide for the transfer of either bank of transformers to either transmission line, and that a glance at the isolating switches suspended from the roof or on the wall will at once indicate just what the connections are.

The principal objection to the entirely open structure is that if a fire should occur, the trouble would almost certainly spread to all the adjacent apparatus, and thus put the whole plant out of commission. To meet this objection, the Shawinigan Water and Power Company have enclosed all the apparatus for each circuit in a separate fireproof room. In so doing they are probably unique in America, although similar arrangements are not unusual on the Continent. Phase barriers are not used, since at high voltages the space between conductors is necessarily so great as to make accidental short-circuit between them practically out of the question.

The Regulations of the United States Bureau of Standards, Washington, Circular No. 54, require that the following spaces shall be left around all conductors which may be occasionally exposed.

Volts.		Space.
750 to 7,500	....	12 in.
7,500 ,, 30,000	....	24 ,,
30,000 ,, 50,000	....	36 ,,
50,000 ,, 70,000	....	48 ,,
70,000 ,, 100,000	....	60 ,,
Over 100,000	....	72 ,,

Since such troubles as do occur are mainly in the oil circuit-breakers, these alone have been separated off in some recent Continental installations. The switchrooms are so arranged as to be accessible from all sides, without entering other compartments containing live apparatus. The doors are fitted with sills, and a drain is provided in the floor to carry burning oil clear of the building.

Through insulating bushings constitute a very great item in the cost of high-voltage cell work and apparatus. Porcelain alone, which is almost universally used on low voltages, becomes out of the question at higher pressures, due to the difficulty of firing properly bodies of sufficient thickness to withstand puncture.

Large porcelain shells filled with paraffin wax, bitumen, or heavy oil have been used to a great extent, the filling medium being relied upon to withstand puncture, while the porcelain itself presents a sufficient creepage surface. These filled insulators possess the property of self-healing after puncture to quite a remarkable degree, the heat of the leakage current melting the wax or bitumen and causing it to flow together again. In the first case the oil-filled type gave much trouble, due to the difficulty of making a perfectly oil-tight joint, and this was greatly aggravated on very high voltages where the porcelain shell had to be made in three or more pieces. Considerable improvement has apparently been made in recent years.

Micarta and other materials of a similar nature have also been used to make what may be termed the " bulk " type of insulator, i.e. one in which mere thickness of dielectric is employed to prevent puncture. The potential gradient through an insulator is not uniform, so that as the voltage increases the thickness of dielectric necessary increases very rapidly. The curve, fig. 23,

indicates the average breakdown voltage per thousandth of an inch for a certain dielectric, which to a greater or less degree is typical of all dielectrics.

The Westinghouse Company introduced many years ago the condenser terminal, in which the insulation is divided up into a series of steps, the voltage across each of which is kept to the same figure. The steps are usually designed for about 10,000 volts test pressure. By controlling the potential

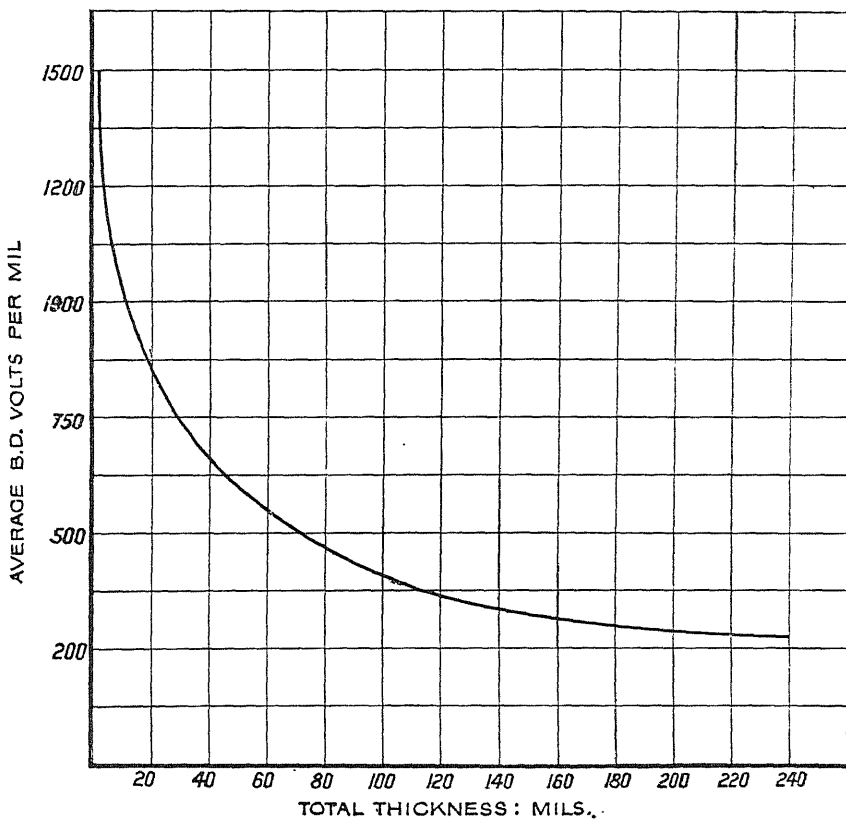


Fig. 23.—Curve showing decreasing Average Values of a Dielectric with increasing Thickness

distribution in this way, the dielectric is employed to maximum advantage, and a much smaller insulating bushing is the result.

This bushing is made of micarta, the layers of tinfoil which form the condenser plates being served in as the process of winding the micarta proceeds. As the diameters of successive layers increase, the lengths of tinfoil decrease, so as to properly balance the capacity of each condenser in relation to its neighbours. The final metal layer is made with banding wire, which presents a strong surface on to which mounting clamps may be fastened.

The exposed ends of the condenser bushing are enclosed in a tube of micarta, and the space between filled with a special insulating compound.

Where the bushing is to be used out of doors the micarta tube is replaced by one built of a series of porcelain rain shields. (See fig. 24.)

With high-voltage work, even more than with apparatus at low pressures, a cubicle must be properly enclosed to be of any real service. In Continental practice it will often be found that the cost of through bushings has been saved by taking leads through large holes in the structure. Since accidental contact between conductors is a small risk, the main function of the high-voltage cubicle is to prevent spread of fire. A structure with large clearance holes can hardly be considered adequate from this view-point.

Since the cost of insulators for high voltages is quite large, designs must be schemed so as to reduce the quantities required to a minimum. The currents to be handled are small, so that suitable solid conductors would in any case have little stiffness. Moreover, the critical voltage for the formation of corona varies with the diameter of conductor. Tubular conductors are consequently almost exclusively used for high-voltage work. Standard copper tubing is generally employed, although in some cases iron gas-pipe has been adopted. With small currents there is no objection to this. The tubes should terminate in spheres, and all clamps at branch connections or supporting insulators be carefully rounded off to prevent the formation of corona on the edges or points which would otherwise be left.

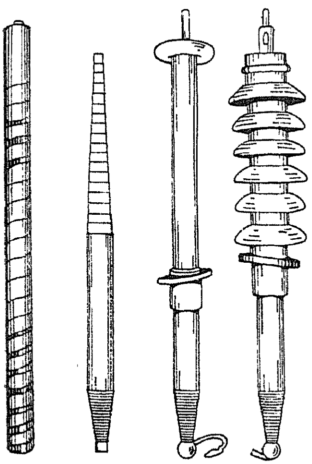

A B C D

Fig. 24.—Condenser Terminals

A, After winding. B, Steps turned to length. C, Complete indoor bushing. D, Complete outdoor bushing.

Insulators should be of such profile as to conform to the stress lines of the electrostatic field as far as possible. Corrugated porcelain insulators have now been shown to possess no advantages over those which are entirely smooth, and the latter represent the more modern practice. Whether indoor or outdoor insulators are used the height is approximately the same. In fig. 25 is given a curve indicating the desirable clearance to earth which should be obtained.

Once an open framework had been found feasible it was a natural step to arrange the apparatus to withstand weather conditions, and omit the building altogether. The first large switching equipment along these lines was built in 1909, near Hamilton, Ontario, Canada, on the system of the Dominion Power and Transmission Company. In view of the severe winters experienced in that district concrete sheds were erected above the oil switches to protect them from the worst of the weather. It was found to be a useless device, however, as during a blizzard snow piles up over the switches despite the canopy. The switch insulation stood up to such treatment perfectly, and since this first installation no attempt

has been made to provide special weather protection in addition to the ordinary weatherproof terminals.

The use of outdoor equipment has grown to such an extent that in probably 80 per cent of the installations in the United States to-day, all transformer and high-voltage switchgear are out of doors. In Canada the practice is not so widespread, not on account of the weather trouble under normal conditions, but rather because cover is essential when carrying out repairs in the winter.

Ordinary switch oil thickens at about zero C., so that it becomes

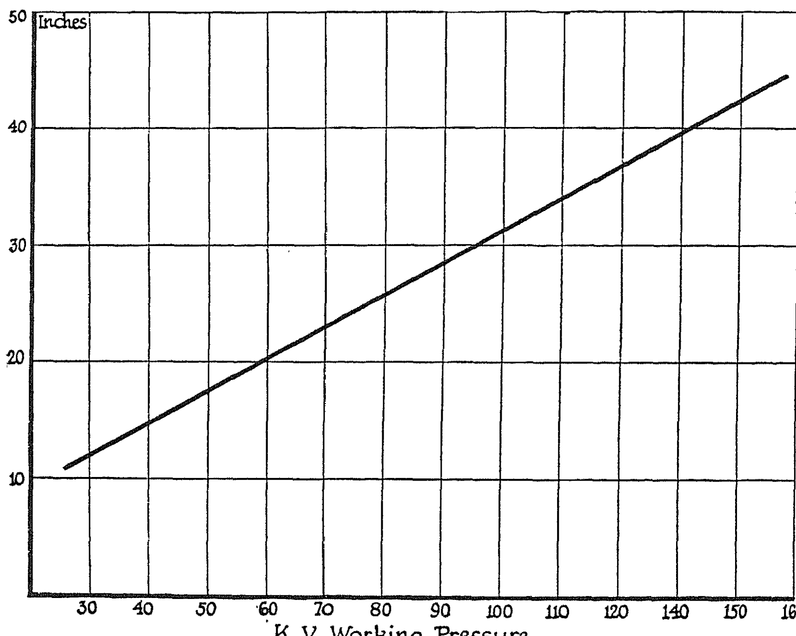


Fig. 25.—Curve showing Desirable Clearance from Conductor to Earth

necessary to use a special oil with a low freezing-point during the winter. In some places where conditions are severe, small heating resistances are installed in the bottom of the switch tanks to keep the oil fluid. The no-load losses of a transformer are sufficient to render it unnecessary to make special provisions in that case.

The steel framework used for supporting apparatus out of doors is much the same as that used for an open construction indoors, although more is necessary, since indoors the walls and ceilings may be used for supports. The spacings of conductors are usually more liberal, desirable minima being indicated in fig. 26. For outdoor work these are frequently exceeded. It follows that the total ground space will be greater with an outdoor lay-out than with the corresponding indoor scheme.

The spacings suggested are on the assumption that the equipment is at or near sea-level. At high altitudes greater clearances may be desirable.

The curve, fig. 27, indicates the approximate relation between flash-over voltage and altitude. This should be taken into account when using the curves in figs. 25 and 26.

An excellent idea of the relation between indoor and outdoor schemes is given by reference to figs. 28 and 29. A power station was planned to

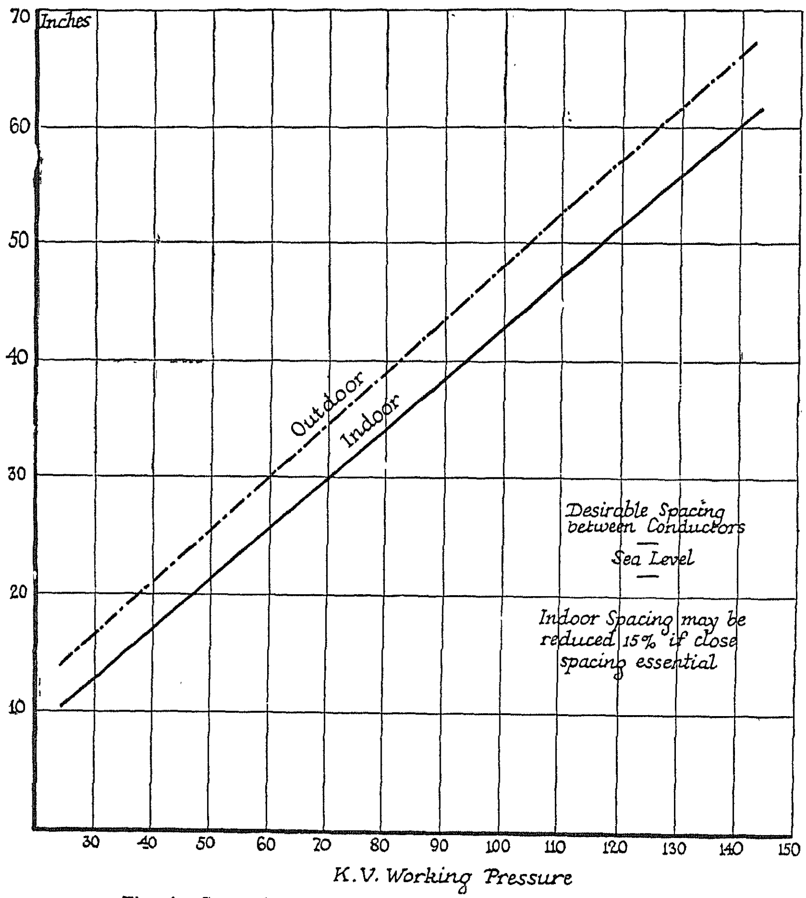


Fig. 26.—Curves showing Desirable Spacings between Conductors in Air

Chain line = outdoors. Full line = indoors.

have six 22,500-k.v.a. 11,000-volt generators, transmission being either at 110,000 volts or 154,000 volts.

Corresponding to each generator was a bank of three 7500-k.v.a. single-phase transformers. The duplicate high-tension bus-bars were sectionalized in the middle, and from each half were two outgoing transmission lines equipped with electrolytic lightning arresters. Alternative schemes were drawn up for the transformers and high-voltage switchgear located indoors or outdoors. The salient features are tabulated.

Space occupied by the lightning arrester equipments has been neglected

	Indoor.		Outdoor.	
	110 K.V.	154 K.V.	110 K.V.	152 K.V.
	ft.	ft.	ft.	ft.
Overall length of building or structure	320	320	430	524
Overall width of building or structure	36	44	66	80
Ground space occupied, square feet	11,520	14,080	28,380	41,920
Height of building or structure	64	76	60	74

in each case, since it does not affect the size of structure required in the lay-outs adopted. The over-all length of the outdoor structures is considerably increased on account of the connections from the oil switches to the selectors, and thence to the duplicate bus-bars. Opposite phases pass in such a way as to double the spacing required on the circuit connections tapping from the main bus-bars. Despite these considerations, the 1918 estimated cost for either outdoor scheme was 13 per cent less than the corresponding indoor lay-out.

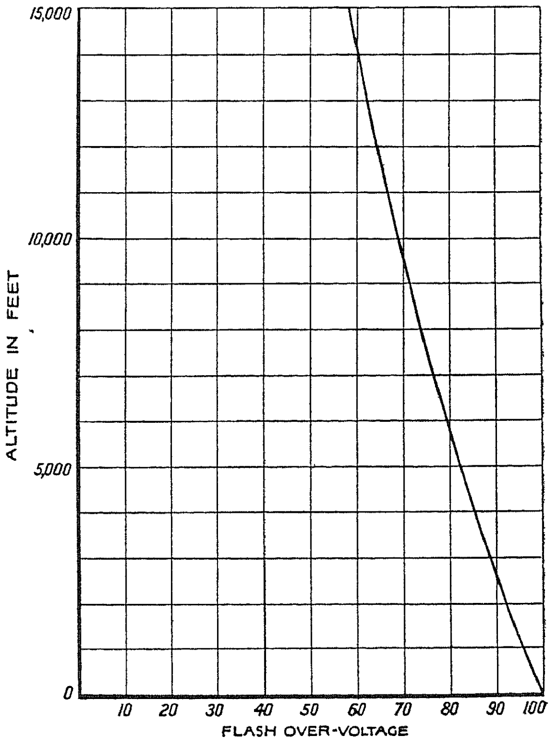


Fig. 27.—Curve showing Relation between Flash-over and Altitude

In order to furnish a rather more definite idea of space requirements, a large number of installations have been analysed and the results plotted in curve, fig. 30. This data must necessarily be regarded as approximate only, since a wide variation exists in conditions which affect the space occupied by the switchgear. There is little difference between single and double bus-bar arrangements when these are on pipe structures indoors. In Continental practice, where cubicles are employed, the difference is marked, and it is interesting to note that in the average case a single-bus outdoor structure occupies less space than the corresponding cubicle work.

To get a common basis, lightning arresters have been omitted in all

cases, since with outdoor structures these are usually outside the steelwork.

With most outdoor substation equipments it is necessary to provide a small operator's house, in which may be located the control switchboard, and also the battery and motor generator set which are required for the remote electrical control of oil switches. As a rule, the transformers are of the oil-immersed self-cooling type, as these require a minimum of supervision. Where water-cooled transformers are employed, the circulating pumps also may be located in the operator's house.

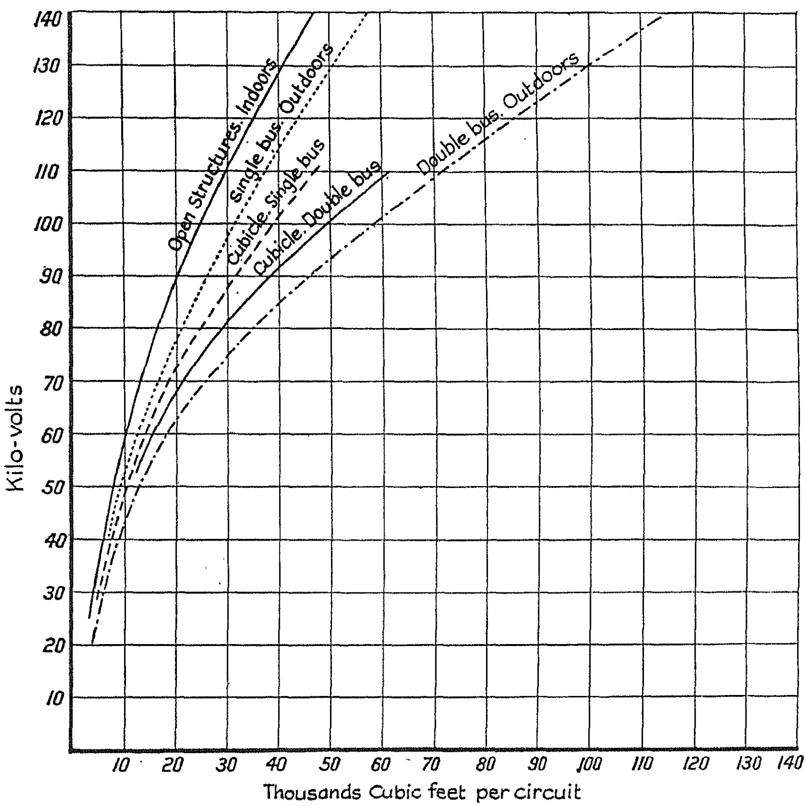


Fig. 30.—Approximate Space occupied with Different Forms of Construction

It is sound practice in a large installation to make such arrangements that individual pieces of apparatus can be taken under cover for repair. Oil switches and transformers may be mounted on small platforms, between which is laid a track for a transfer wagon. In any case it is desirable to mount the apparatus clear of the foundations, so as to facilitate painting underneath, and to prevent rusting up.

In fig. 31 is shown two banks of single-phase step-up transformers, and the corresponding high-voltage switchgear. In this case structural steelwork has been reduced to a minimum by stringing conductors from

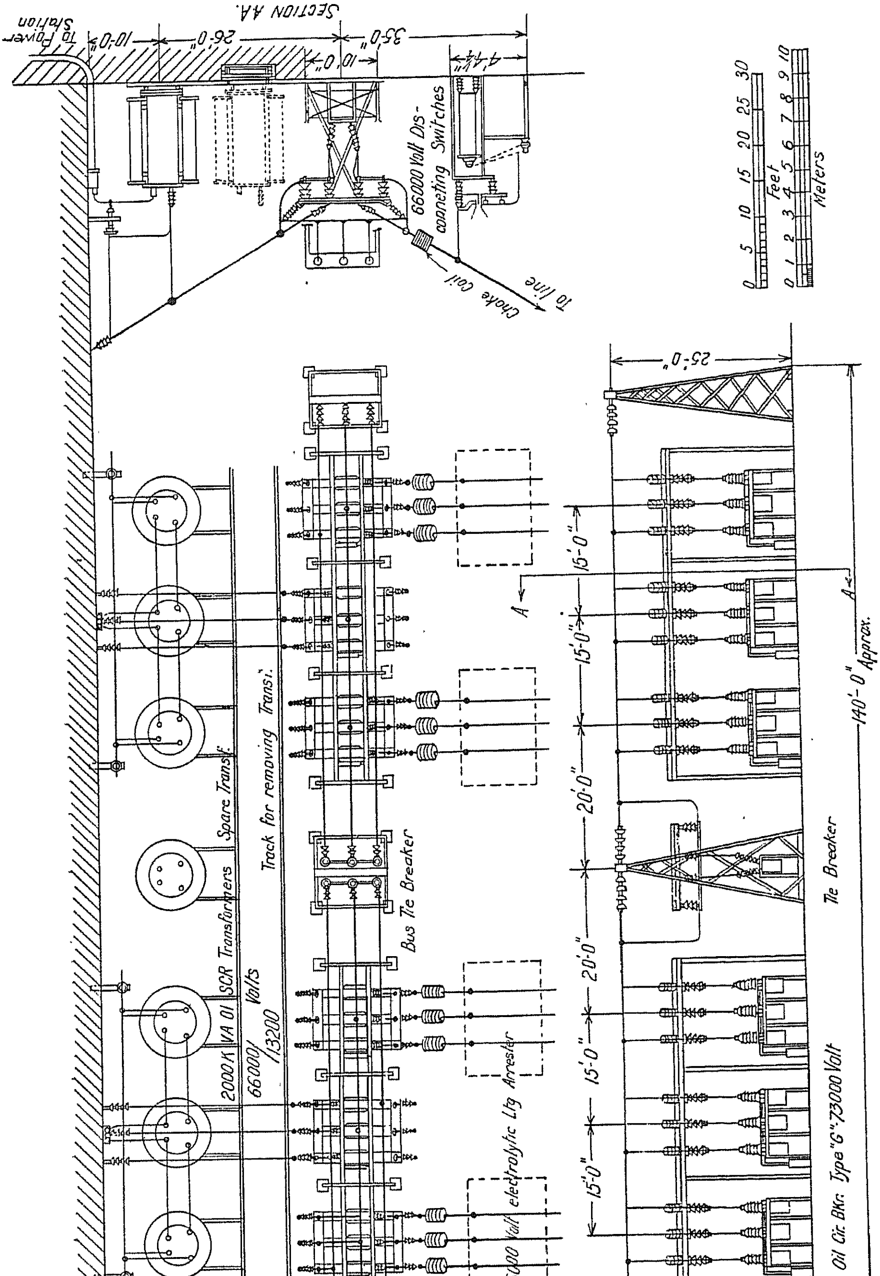


Fig. 31.—66,000-volt Outdoor Substation

the power station wall and from the first transmission tower. The great economy of such an arrangement is evident at first glance. It will be noted that a track is provided so that any transformer unit may be removed inside the station for repairs.

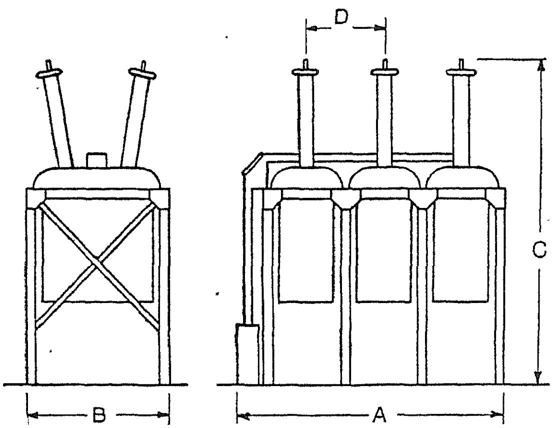


Fig. 32.—Outline of High-voltage Oil Switch

Insulation does not present a very serious problem, since the usual petticoated form of insulator can be made to stand up well, even though covered in snow and ice.

Dimensions of high-voltage oil switches do not vary widely, since they are dictated rather by insulation requirements than those of breaking capacity. In the following table average figures are given referring to fig. 32.

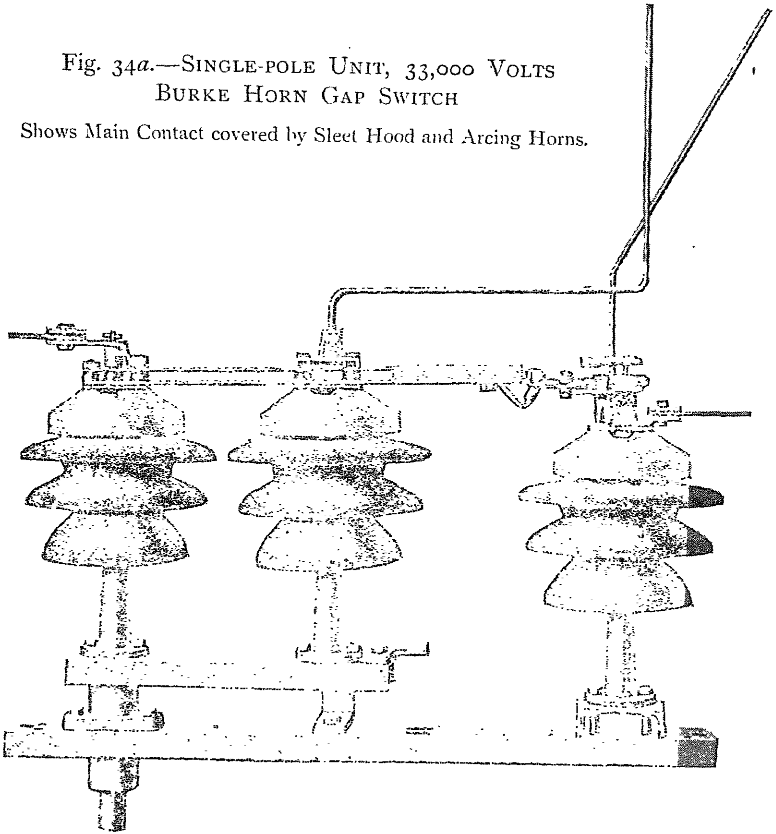
Volts.	A.	B.	C.	D.
	Inches.	Inches.	Inches.	Inches.
25,000	87	30	84	24
37,000	94	30	93	25
50,000	102	33	110	27
73,000	123	36	120	40
95,000	143	48	124	48
115,000	202	70	157	56
135,000	272	85	170	75
155,000	272	85	183	84

For the purpose of preliminary lay-out drawings, the following dimensions of isolating switches (fig. 33) may be taken as representing an average for either indoor or outdoor use.

Voltage.	A.	B.
	Inches.	Inches.
25,000	10	24
37,000	15	30
50,000	18	36
73,000	25	40
95,000	32	50
115,000	37	60
135,000	44	70
155,000	48	80

Fig. 34*a*.—SINGLE-POLE UNIT, 33,000 VOLTS BURKE HORN GAP SWITCH

Shows Main Contact covered by Sleet Hood and Arcing Horns.



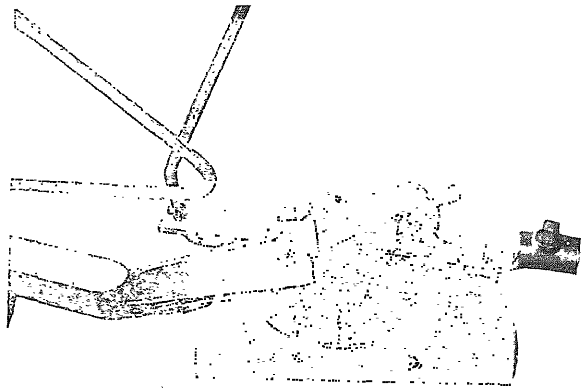


Fig. 34*b*.—CLOSE VIEW OF MAIN CONTACT OF BURKE HORN GAP SWITCH, WITH SLEET HOOD REMOVED

This protected copper-leaf Brush Contact makes a perfect operation certain under all conditions.

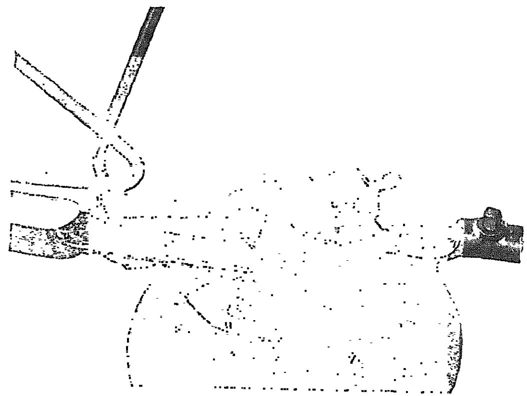


Fig. 34*c*.—BURKE TYPE SWITCH, SHOWING ICE-BREAKING ACTION

The greatest trouble experienced is due to ice forming over the contacts of isolating switches, and thus preventing their being opened. Various forms of shield have been adopted with more or less success. About the best device so far produced is embodied in the horn-type switch built by the Railway and Industrial Engineering Company of Greensburgh, Pa., U.S.A. This is shown in fig. 34, *a*, *b*, and *c*. It will be seen that in the first movement of opening the contact is given a twisting wrench which effectively breaks any ice which may have formed under the shields. The switch arm is then free to swing open to the full extent.

This switch serves also to illustrate a further step towards cheapening

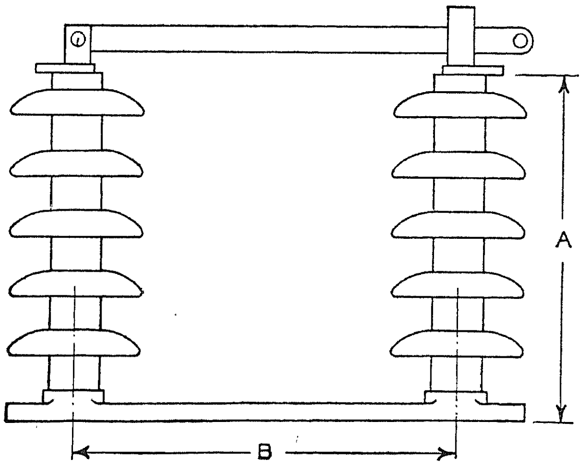


Fig. 33.—Outline of High-voltage Isolating Switch

high-voltage switching apparatus. Several such designs have been evolved, in which the arc is transferred to horns, and there broken as in the horn-type lightning arrester. As the horns can be and are moved apart once the arc is transferred to them, considerable powers may be interrupted on such switches. The one illustrated has been demonstrated capable of breaking 4000 to 5000 k.v.a. power load on the 44,000-volt lines of the Georgia Railway and Power Company. The average arcing time was 6 sec., and, contrary to common opinion, the voltage surges set up under these conditions were less than those caused by an oil circuit-breaker on the same duty.

Originally made of the non-automatic type, for use with fuses in series, automatic overload attachments are now built, as well as remote electrical control mechanisms. The horn-type apparatus can, therefore, be applied to the same service as can an oil circuit-breaker, within its limits of breaking capacity. In known cases transformer banks of 4000 k.v.a. capacity are protected by these automatic horn switches.

NOTE.—*Figures 3a, 3b, 6, 8, and 9 of this chapter in pocket at end of volume.*

CHAPTER XI

Station Lay-outs

Station lay-outs; automatic generating stations; Thury system

1. Station Lay-outs.—The character of the development has a direct bearing on the general lay-out adopted. In a low-head station the available space is usually strictly limited by the width of the dam on which it is built. This, in turn, is determined by the space required for the turbines, since it will hardly pay to make the station floor any larger than is required for the proper installation and handling of these units. In a high-head proposition the station site can usually be chosen so that ample ground space is available.

In consequence, it is usually found that in the low-head plant there is a tendency to locate the switchgear and possible transformers either on floors above the machine-room, or, as is becoming more common, in an entirely separate building on the river bank.

In arranging the generating sets, it is usually best to place them in a row down the length of the station. Practically no difference is made whether horizontal shaft sets have the shafts parallel or at right angles to the long axis of the station, but the former arrangement is usual in high-head plants using impulse-type water-wheels.

In every case sufficient room must be allowed for completely dismantling one set. The most convenient method is to space out the machines so that sufficient space for this purpose exists between each pair of generators. Space is often saved, however, by having this repairing area at one end of the plant, in close proximity to the workshop.

Where a common exciter system is employed, the machines should be central in relation to the generating sets, so as to reduce the cable runs. With individual exciters the control switchgear should similarly be placed adjacent to the corresponding generators.

The total space occupied varies very little with the character of the development, however. A reasonable average will be to allow for the main machine-room about 13 c. ft. per k.v.a. of generator capacity. In a very compact lay-out this may go as low as 8 or 9 c. ft, while certain plants planned on very liberal lines have occupied up to 25 c. ft. per k.v.a.

Since nearly all hydro-electric stations operate in conjunction with high-voltage transmission lines, the space occupied by switchgear and trans-

formers also approximates reasonably to an average. In this case the average is about 10 c. ft. per k.v.a. of generator capacity, irrespective of transmission voltage, the limits in cases examined being from 15 to 5 c. ft.

Although in the typical stations which are illustrated hereafter only the Southern Power Company's Wateree plant has all transformers and high-tension switchgear out of doors, this must be recognized as the coming practice. Isolated examples already exist in Norway, France, Italy, and Spain, and their successful operation will undoubtedly be followed by many European installations. It has even been proposed to place the whole generating plant outside, merely providing a portable cover for use during repair work. The recently planned Mussel Shoals development in Alabama was originally schemed along these lines. It has finally been decided to adopt the conventional type of station building, but the completely outdoor generating station will doubtless arrive in the near future.

Conditions vary to such an extent that it is quite impossible to lay down rules for proper station design. A study of typical station lay-out drawings serves this purpose better than much written matter. Certain essential features, however, require special consideration.

In small- and medium-size plants no special provision needs to be made for ventilating the generators. The fans on rotors can circulate sufficient air drawn from the room to keep the machines cool, and at the same time the room temperature will not become excessive. A loss of 1 kw.-min. will heat up 1800 c. ft. of air through 1° C. when starting from ordinary room temperatures. Where forced ventilation is not resorted to the difference in temperature between incoming and outgoing cooling air should not exceed 18° C., and is preferably kept lower, so that the actual air volume necessary per kilowatt of generator loss will be from 100–150 c. ft. per minute.

Although special means are not necessary for ventilating small machines, certain precautions must be observed. The machine should not stand over or partly in an unventilated pit which will act as a pocket for heated air and prevent adequate cooling of the bottom coils. Similarly, the generators must be kept clear of walls, and especially of overhanging structures which would interfere with proper convection. On larger machines it is essential to leave nothing to chance, and arrangements are made to draw from outside the building all the cooling air required. This may be returned to the exterior in hot weather, or may be discharged into the power station in the winter. Each machine is treated as an independent unit with its own ventilating duct.

It is general to arrange so that outside air comes into the pit beneath the generator, which is sealed off in such a way that all air must be drawn through the machine frame, and thence discharged. Air filters are not usually necessary with the atmospheric conditions prevailing around a hydro-electric plant.

The air ducts to each machine should be kept as short and straight as possible, and unavoidable bends made with a wide sweep. The inside radius at a bend should not be less than three-quarters of the duct width. The duct area should be such as to ensure a maximum air velocity of 1000 to 1250

ft. per minute. Special fans are not usually necessary to obtain a sufficiency of air. The difference in level between intake and discharge can generally be arranged to create an ample natural draught. The exception to this general case is a slow-speed machine, where separate fans may be required. In this case a common air-supply chamber may be adopted, with a stand-by fan in addition to that required for normal working. Means should be provided so that the duct from an idle fan, or to an idle generator, can be closed off, and thus prevent loss of air. The pressure to be maintained in such a forced-draught system is quite small, sufficient only to ensure a definite current of air to the machine.

The large volume of oil in transformers is generally held to constitute a special fire hazard. When they are placed inside the station building, it is customary to isolate them within separate fireproof cells, the front of which can be closed by automatic fire doors. In certain Continental stations these cells have been arranged so that they are parted off completely from the main machine-room, the opening being in the outer wall of the station, with the transfer track outside. Where the transformer must be under cover, this arrangement is excellent, although it usually involves special ventilating arrangements, since the fire doors must frequently be closed on account of the weather. This, of course, only applies to oil-immersed self-cooled transformers.

Self-cooled transformers in open-fronted cubicles should stand at least two feet clear of all walls. Where the fire door may be closed on account of weather, the transformer must be supplied with cooling air at the rate of about 145 c. ft. per minute per kilowatt loss. In such cases, however, it is more usual to employ water-cooled transformers, or preferably to use transformers with external oil coolers. The latter construction is free from the risk of breakdown due to the presence of water in the oil, which may happen with a defective water-piping system.

Arrangements must be made for the easy handling of large power transformers. Where these are not under the main crane they should be mounted on rollers, and should stand on an elevated platform, in front of which is run a rail track for a transfer truck on to which any transformer unit can be rolled for transfer to the repair shop.

Too close attention cannot be paid to the wiring of a power station, both as regards main conductors and also the auxiliary connections. In America it is almost standard practice to draw everything through fibre conduits which have been laid in the flooring before the concrete has been poured. Such an arrangement is very inflexible, since changes in connections involve either abandoning a conduit and laying new, or else chipping out much building material. On the other hand wiring so run is practically fireproof.

High-voltage conductors will always be carried on insulators and entirely open. For the main low-tension conductors also this practice is desirable, providing that special tunnels can be employed. Trenches in the main floor covered with chequer plate are bad, since water may enter when the floor is being washed down.

The small wiring from switch cubicles to control board should always be run in armoured multi-core cables, which can then be carried through the main cable tunnel, or the ordinary passage ways of the building.

2. Typical Lay-outs.—The following pages give details of a number of typical station lay-outs.

* *New England Power Company.*—The stations known as Nos. 3 and 4, situated on the Deerfield River, are practically duplicates. The essential difference is in the location, No. 3 being built on an extension of the dam

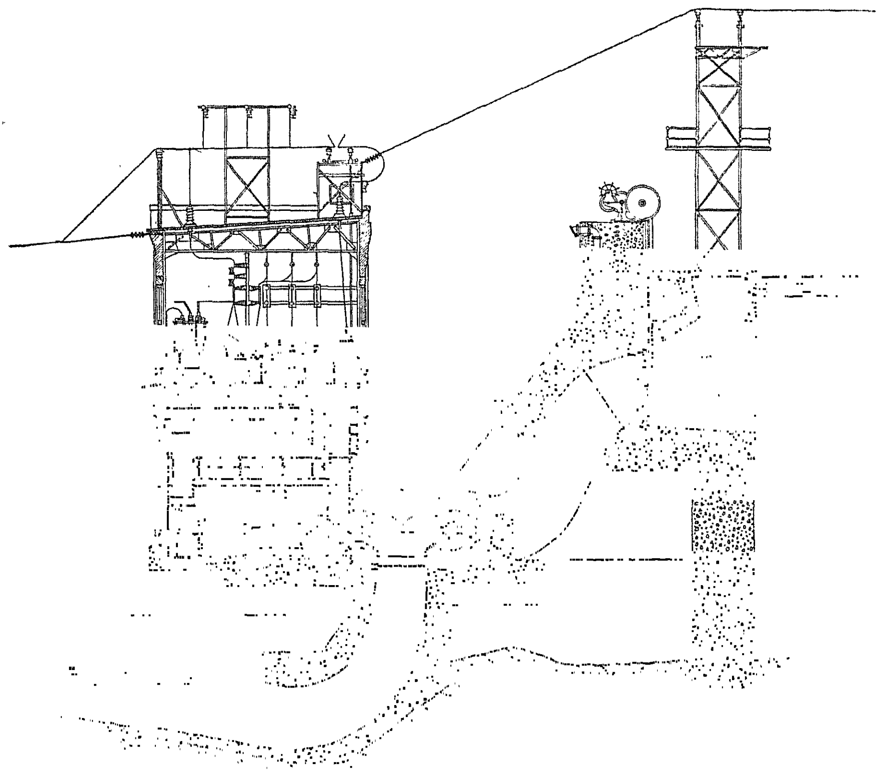


Fig. 1.—New England Power Company. No. 3 Station

structure (fig. 1), while in the case of No. 4 water is received through steel penstocks about 160 ft. long.

In each case the horizontal shaft water-wheels are located outside the building, through the wall of which a shaft connects to the generators. This arrangement is very economical of building space.

The three water-wheels in each station are of the double-runner central-discharge type, running at 257 r.p.m. under a head of 60 ft. These are coupled to 1600 k.v.a., 60 cycle, three-phase, 2300 volt generators. The shafts and bedplates of these sets are made extra long so that the entire stator may be racked clear along slides when repairs are necessary.

* Illustrations reproduced by permission of the New England Power Company.

A common system of excitation is adopted, D.C. being furnished from two motor-generator sets, either of which is large enough to take care of the three generators in the station. A small battery permanently floats across the excitation bus-bars, this being primarily intended for oil switch operation. It is, however, large enough to supply excitation current for a few minutes in case of a total shut-down of the system.

Both exciter sets are served from a single oil switch from the 2300-volt bus-bars (fig. 2). The failure of this switch would, therefore, involve a complete shut-down until it was replaced.

All oil switches on the 2300-volt system are non-automatic. Power is stepped up to 66,000 volts, at which pressure the stations are tied in with all others on the New England Power Company's system. The 66,000-volt feeders are run in duplicate, and the circuit-breakers are fitted with cross-connected overload and reverse relays.

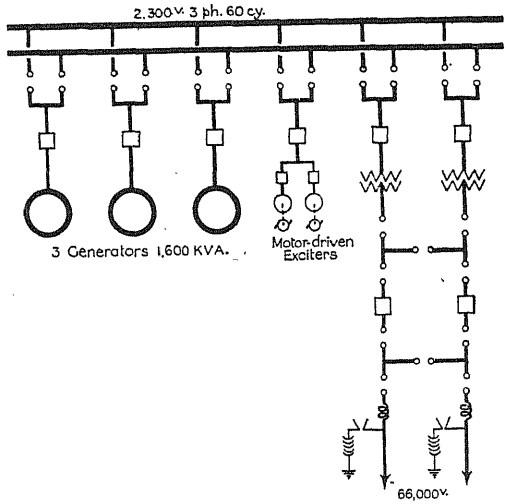


Fig. 2.—New England Power Company, Shelbourne Falls Diagram of Connections

The control switch-board is centrally located on the machine-room floor, with the low-tension switch cubicles at one end of the main floor. The upper floor is devoted to the 66,000-volt switch-gear and the transformers. The battery is located on a light gallery above the 2300-volt switch cubicles.

The lay-out of these stations furnishes a good example of the methods which may be adopted when low first cost is of primary importance, and where absolute safety and continuity of operation may have to be sacrificed to some extent to secure this economy.

* *Olten-Gösgen Station, Switzerland.*—This station was only put into service at the end of 1917, and furnishes an excellent example of up-to-date Continental practice. As will be seen from the plate (figs. 3*a* and 3*b*), only the machine-room stands on the dam, the switch and transformer building being built as an annex on the bank on the down-stream side.

The building is laid out for eight generating units, of which six are at present installed. These are all 7000 k.v.a., three-phase, 50 cycles, 8000 volts, driven by Francis type single-runner water-wheels at 83·3 r.p.m. under a head of approximately 52 ft.

In arranging the lay-out, unusually generous space allowances (from the

* The contractors for this station were the Motor A. G. für angewandte Elektrizität, Baden, Switzerland, who furnished the illustrations and gave permission for this description.

British point of view) have been made, but by this means several novel features have been incorporated. The machine-room contains approximately 25 c. ft. per k.v.a. of final generating capacity. At one end is left a clear working space in which repairs can be effected. To this point rails are run from the transformer room, so that any transformer unit may be taken on its transfer truck to a point at which it can be handled by the main travelling crane. A vacuum tank is provided, this being large enough to hold a complete transformer. A second set of rails connects the machine-room and the workshop, where a full set of machine tools is available.

Separate ventilating air ducts are not installed, but the generators are mounted on pedestals, clear of the floor, so that air can be drawn from below and discharged through the top of the machine. A cable tunnel is run beneath the machine-room floor, and thence to the low-tension switchgear annex.

As will be seen from the sectional elevation, the main control-room is at one end of the machine hall, raised high up so as to command a good view. Generator control is centralized on the desk facing the window. Although, normally, all operations are carried out at this point, a second control pillar stands on the machine-room floor, adjacent to each machine, and in case of emergency full control may be effected there.

Transformers and feeders are controlled from a desk switchboard facing the generator desk, and at the back of this are panels for all relays and graphic instruments. All desk tops are of cast iron, and have a dummy diagram cast upon them. Magnetic signals show the position of all oil and isolating switches.

It will be noticed that a shallow floor is provided beneath the control-room floor. In this space all small wiring is run, and bunched into multi-core cables to the switch cubicles. The wiring inside the desks is thus kept as clear and simple as possible.

All generators are protected with reverse power time-limit and overload time-limit relays, while the other circuits have overload time-limit relays only. These relays work in conjunction with automatic-current limiting regulators on each generator, so that under fault conditions the excitation is reduced as low as possible before any circuit-breaker operates. This, or some similar device, is very commonly used in Continental practice to limit the rupturing capacity necessary for the circuit-breakers.

As in the machine-room, ample space has been provided in the transformer and switch house. This building is subdivided into several fireproof sections, which are fitted with fire doors to entirely enclose each section. This necessarily involves the employment of greater space, but distinctly improves the safety of the plant as a whole. The floor-space devoted to the high-voltage switchgear could probably have been considerably reduced. Referring to the section AB, a more usual arrangement would be to raise the bus-bars, and to put the transformer and feeder oil switches beneath. This would avoid the rather awkward crossover beneath the floor in the bus-bar room.

The large room space devoted to the horn lightning arresters would be saved in standard American practice where all arresters would be out of doors.

Beneath all oil switch and transformer tanks are drain sumps to lead off any oil which may leak out. Within each fireproof room the switch tanks are again enclosed in concrete cells with sheet-steel doors. A passage runs at the back of all oil switches (from which it is separated by a concrete wall), the switches being operable from this point, either electrically or by hand-wheel.

A magnetic indicator is placed in each 8000-volt selector switch cubicle to show the position of the corresponding oil switch on the floor below. In operation the switches are paralleled on both high- and low-tension sides.

* *Wateree Generating Station.*—The Wateree plant of the Southern Power Company is the most modern of large American water-power stations, having only been put into operation in December, 1919. It presents many features of novelty.

The station is erected on an extension of the concrete dam, in which are formed the wheel chambers and draft tubes (see fig. 4). This portion of the concrete work is reinforced with steel. The building houses the generators and low-tension switchgear only, the step-up transformers and 100,000-volt switchgear being outside.

There are five 14,000 k.v.a., 6600 volt, three-phase, 60 cycle generators, driven by Francis turbines of the single-runner vertical-shaft type at 100 r.p.m. The normal head is 63 ft., operating range being from 55 to 75 ft.

Cooling air for the generators is brought through openings in the station wall, between the transformer brackets, and thence into an air-way which runs beneath the generator floor, through the whole length of the station. Air is thus drawn from beneath the generator frame, and the hot air discharged into the machine-room.

Each generator has its own direct-driven exciter, and as no series rheostats are used, the field slip rings are mounted on the upper end of the shaft, directly above the commutator. A spare motor-driven exciter supplied from the station service transformer can be connected in place of any unit by means of jumper cables.

Control is effected from a desk-type switchboard located on a gallery at that end of the power station nearest the switching station. It is thus possible to view the high-voltage switchgear from the gallery windows. Generators are hand controlled, no automatic voltage regulators being employed. The exciter shunt rheostats are electrically operated, and are mounted close to their respective generators. Simultaneous control for these rheostats will shortly be added.

Normally each generator and its corresponding transformer are operated as a unit, synchronizing on the high-tension side only. Low-tension transfer bus-bars are located in the ventilating air-way beneath the machine floor level,

* Drawings and description included by permission of Mr. M. R. Kimbrell, electrical engineer of the Southern Power Company.

so that it is possible to connect any machine with any transformer (see diagram fig. 5).

In the usual arrangement the transformers would be located in the high-tension switching station, requiring a considerable length of heavy copper connections on the low-tension side. In this station the transformers are located on masonry brackets built out on the main substructure of the station. The neutral bus-bar for the high-tension side of the transformers is suspended on insulators from these brackets. From the general drawing of the plant (fig. 6) it will be seen that the transformers are spaced out to the generator centres, and that between them have been built small annexes in which are the low-tension generator and transfer circuit-breakers. The run for heavy copper

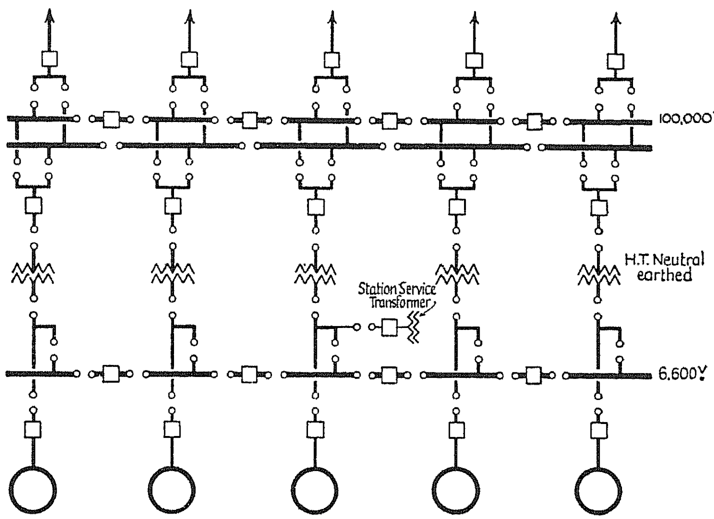


Fig. 5.—Southern Power Company, Wateree Station. Diagram of Connections

connections from generator to transformer has thus been reduced to a minimum. These connections are of bare copper strap, supported on insulators, and are run in the ventilating air passage, an unusual feature in American practice. A very small station building is obtained, the space amounting to only 9 c. ft. per k.v.a. of generator capacity. All transformers are on rollers, and can be taken inside the station for repairs. A pit is provided at one end of the station floor to facilitate the removal of the transformer from its tank.

The high-voltage station is on the river bank, the distance from the power station being dictated by the angle at which the 100-kv. conductors can be strung. This equipment is carried on a reinforced concrete platform erected high on pillars to be above high-water level in the event of floods to which the locality is liable. This platform is level with the generating station floor, and is connected with the station by a raised concrete footwalk. The lattice steelwork for supporting bus-bars and isolating switches is of a type which

has been standardized by the Southern Power Company, and which is employed in all their high-voltage outdoor stations.

Four of the outgoing feeders are taken across the river, connections from the switching station going straight to the crossing terminal towers. The fifth feeder serves to tie in with the system of the Yadkin Power Company.

No lightning arresters are used on any of these 100,000-volt feeders, complete reliance being placed on the general system insulation, and on the ground wire which runs above all transmission towers.

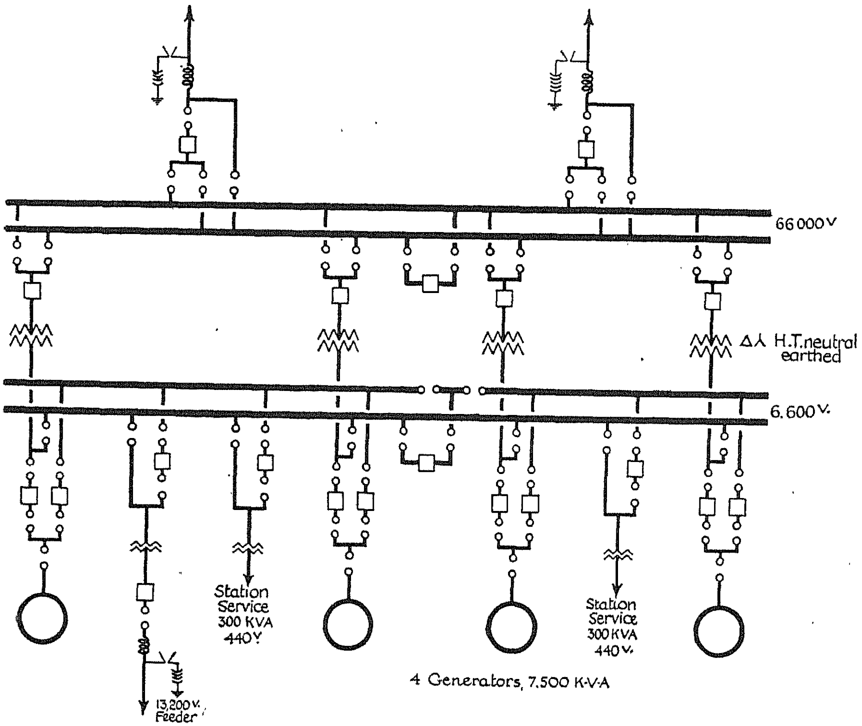


Fig. 7.—Connecticut L. & P. Company, Stevenson Station. Diagram of Connections

* *Stevenson Station, Connecticut L. & P. Co.*—This station has only been put into commission within the past three or four years, and may be considered representative for a plant of medium capacity, in which all high-voltage apparatus is contained within the main building.

At present there are three generating units, each 7500 k.v.a., 6600 volts, three-phase, 60 cycles, driven by vertical turbines which operate under an average head of 95 feet. The station stands upon an extension of the dam structure, on the top of which also runs a main roadway across the river. Space in the machine-room is approximately 10·2 c. ft. per k.v.a., and in the transformer and switch section approximately 11 c. ft. per k.v.a.

The general system of connections is shown in fig. 7. Correspond-

* Drawings reproduced by permission of Mr. Miles, Connecticut L. & P. Co.

ing to each generator is a bank of 3 single-phase transformers, stepping up to 66,000 volts. Power is transmitted overhead to the main switching station of the system at Waterbury, where is also tied in a steam plant of 30,000 k.v.a. capacity.

An air duct, common to all generators, runs beneath the machine floor, air being drawn from outside the building and discharged into the machine-room.

Each generator has its own exciter, the capacity of one exciter being sufficient for two generators. Electrically operated switches, located close to each machine, are connected as shown in fig. 2, p. 150. In addition there is a stand-by motor generator driven from the station service bus-bars, and this can be connected to any or all of the generator fields.

Control is effected from a gallery centrally located on a longitudinal wall, all switches being electrically operated. Electrical gate control is also centralized at this point. In the sectional drawing, attention is drawn to the conduit trench beneath the control desk. This enables a workman to stand at ease when attending to the small wiring. The separate rheostat room opens from the machine-room, and a ventilating duct is taken from the rear of this room to the stairway leading outside the building. All rheostats are hand operated through chain drive.

Each bank of three single-phase transformers stands within a fireproof concrete cubicle. The cubicles open into the machine-room, but roller shutters are furnished so that any bank may be shut off in case of trouble. Sufficient space is allowed so that any unit can be drawn out under the crane in the machine-room. Cooling water for these transformers is taken from behind the dam.

Cables from the generators to the low-tension switchgear and all other wiring about the station is drawn through fibre conduits embedded in the concrete work of the building.

The 6600-volt switchgear is arranged in conventional manner in concrete cubicles. These are arranged symmetrically about the control desk, from which they are separated by automatic fire-doors. Similar doors are arranged midway along each line of cubicles. Although all the switchgear, except the lightning arresters, is inside the building, outdoor type bushings and insulators are employed on account of the dense fogs and mists which prevail. The increase in cost would only be slight, although ordinary indoor apparatus would no doubt have withstood the conditions.

Connections to the outgoing feeders and the lightning arresters are taken through roof bushings. As will be seen the choke coils are mounted immediately before the point at which the tapping is taken to the arresters, an ideal position. Separate horn-type switches are installed to disconnect the lightning arresters, should this be desirable for inspection purposes.

* *Shawinigan Water and Power Company, Station No. 2.*—The plants of the Shawinigan Water and Power Company are located to the north of Trois

* Description and illustrations reproduced by permission of Mr. E. J. Reid, Shawinigan Water and Power Company.

Rivières in the province of Quebec, and are employed to serve the city of Montreal, 87 miles away, through a 100,000-volt transmission system. The first station was in its time one of the largest hydro-electric developments. The No. 2 station was put into operation in November, 1911, and although it has been dealt with in the technical press, it possesses certain features which render a repetition desirable.

The original equipment consisted of two generating units, 14,000 k.v.a., three-phase, 6600 volts, 60 cycles, driven by horizontal-shaft water-wheels at 225 r.p.m. under a head of 145 feet. The turbines are of the twin spiral case type, receiving water at the bottom and discharging inward to a central draft chest. The turbine room is walled off from the main generator room.

There are now five generating units which work in groups of two, with the fifth unit centrally located, and thus able to assist either half of the system. Normally each generator is connected through a reactance coil to its own transformer and thence to the corresponding transmission line. The total reactance is 23 per cent to the high-tension line switch.

Figs. 10, 11, and 12 show only the first installation laid out for three units. The final extension has been carried out on the same lines.

Excitation is obtained from two 400-kw., 125-volt water-wheel driven sets, and a third unit of similar size, driven by a motor served from the station service transformer. In addition it is possible to connect the common excitation bus-bars either to the auxiliary battery provided primarily for oil-switch operation, or alternatively to the D.C. supply in the adjacent power house No. 1. It will thus be realized that the possibility of entirely losing excitation (an occurrence not unknown where a common bus-bar system is employed) is fully guarded against.

Throughout the design of this station continuity of service and safety of operation have been kept to the front. The resulting arrangement is not perhaps the most economical of space, but is of considerable engineering interest.

The transformers are of the three-phase, oil-immersed, water-cooled type, delta-star connected, with the high-tension neutrals earthed through 100 ohms. Each transformer is in a separate cubicle below the machine-room floor level. A portion of the floor is removable, enabling the transformer to be drawn forward and then lifted by the main crane.

The low-tension switchgear corresponding to each generator stands on the main floor level, within a concrete walled room, the arrangement being such as to entirely prevent the spread of fire should one occur above an oil circuit-breaker.

Similarly, the 100,000-volt switch-room is divided up with fireproof walls between circuits, these also separating the oil switches from the rest of the equipment. All disconnecting and selector switches are three-pole mechanically operated from the passage way outside the dividing wall. The design of these switches was developed by the Shawinigan Company's engineers.

Three-pole switches of this kind lend themselves to signal arrangements,

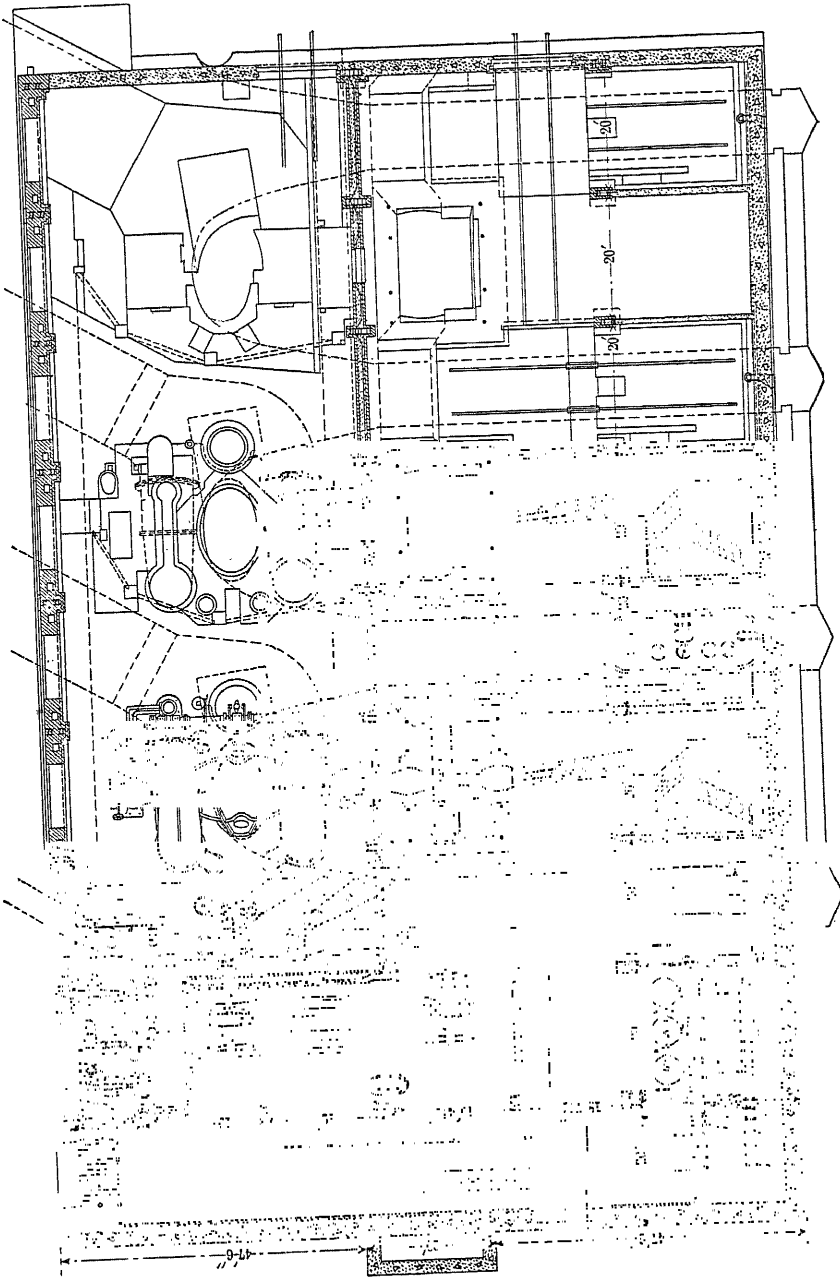
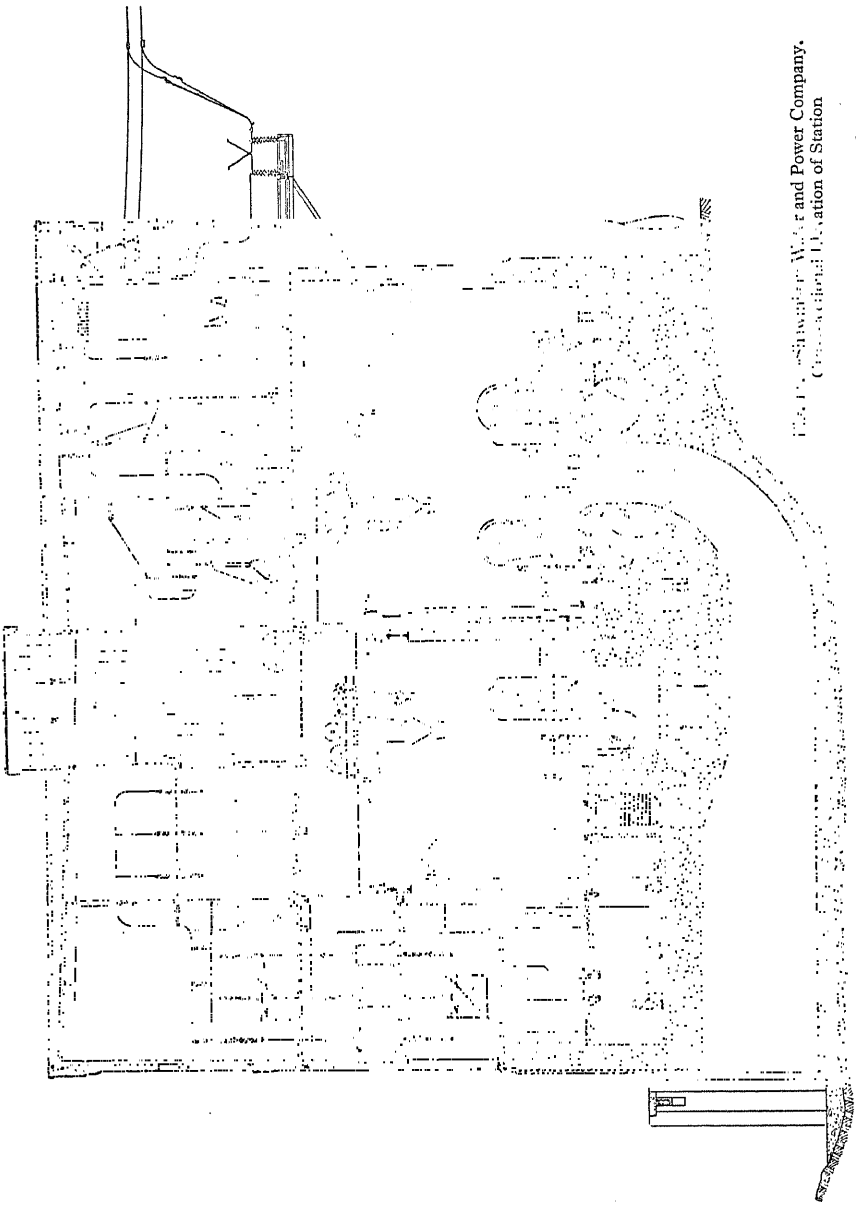


Fig. 10.—Shawinigan Water and Power Company. Plan View of Station No. 2

and pilot lamps in connection with the dummy diagram on the main control desk indicate the position of every oil and isolating switch in the station.

All generators have balanced current protection, with automatic field switches. The transformers also are protected with balanced current



[illegible] W[illegible]r and Power Company.
[illegible]ation of Station

apparatus, while on the high-tension lines is employed a peculiar system of protection, which operates by earthing momentarily any circuit which develops a fault, and thus causes the circuit-breakers to open on overload.

3. Comparison of Connection Systems.—A review of the systems of connection employed in the five typical stations described will be of interest.

The plants at Shawinigan and at Wateree are of the same generating capacity and in many ways are similar. In each case normal operation is to connect each generator to its own transformer and 110,000-volt transmission line. Each has a single 6600-volt transfer bus and duplicate bus-bars on the 110,000-volt side.

With either arrangement it is possible to alter the grouping of generators, transformers, and feeders without interrupting supply, the final separation of circuits being accomplished with an oil switch. Normal requirements as to flexibility are therefore served, although it will be noted that in the case of Wateree a smaller number of oil switches is required than for Shawinigan.

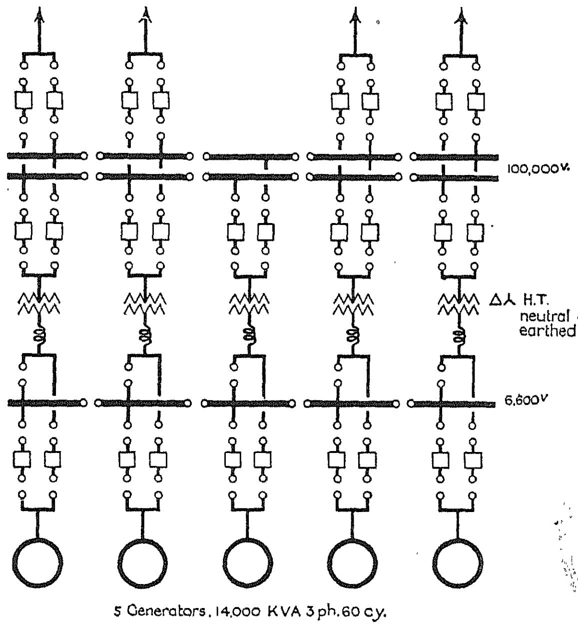


Fig. 12.—Shawinigan Water and Power Company. No. 2 Station Diagram of Connections

The duplication of oil switches at Shawinigan, however, makes it possible to isolate any oil switch for repairs, cleaning, or change of oil without shutting down the unit to which it is connected. This cannot be done with the Wateree connections, where it is essential to arrange for the temporary transfer of load through some other circuit when it is desired to work on the oil switches.

In the Stevenson station, generator and transformer are worked as a unit and are paralleled on high-tension bus-bars. This arrangement is increasingly popular in this country, in stations where the bulk of power generated is to be transmitted to a distance at high tension, and where the capacity of outgoing feeders cannot be made uniform or be estimated closely beforehand. In Stevenson re-grouping of machines and transformers is made possible by the use of a bus-tie oil switch on both low- and high-tension sides.

A main and auxiliary bus-bar is used on the low-tension side to facilitate operating local feeders off any combination of generators.

The connections employed in all these three stations do not lend themselves conveniently to balanced current protection of transformers, since the same pair of oil circuit-breakers are not always used on high- and low-tension sides. To be more explicit, let us consider the Wateree diagram. Normally, generator 1 works with transformer 1, and generator 2 with transformer 2, and so on. If the transfer bus be in use generator 1 may be working with transformer 2, in which case the balanced relays across the latter would be required to operate transformer 2 high-tension circuit-breaker, and also generator 1 circuit-breaker.

If coarse relay settings are permissible, a selector switch can be employed to change over the relay wiring when the transfer bus is in use. Otherwise it would be necessary to balance each high-tension series transformer against every low-tension protective transformer, a long and expensive matter.

From this point of view the switch arrangement at Olten-Gösgen is preferable, since here every transformer has its independent oil circuit-breaker on high- and low-tension sides. Generally, however, the extra expense involved is such that engineers prefer to have their protective relay temporarily cut out, or set high during the time the transfer bus-bar system is in use.

The duplicate high-tension transfer bus-bar system at Olten-Gösgen is an unusual elaboration, especially in a station having so few feeders. On the low-tension side, the duplication is necessary to deal with the local feeders at generating voltage.

The connection system employed at Shelbourne Falls is an excellent one for a comparatively small plant, apart from the exciter control to which reference has already been made. Particular note should be made of the arrangement of high-tension selector switches which makes it possible to isolate either oil switch for cleaning, while keeping both of the transformers and the lines in commission.

4. Automatic Generating Stations.—A definite step in engineering advance was taken when in October, 1917, the first automatic generating station was set in operation. This is on the system of the Iowa Railway and Light Company, where it operates in parallel with a steam plant of some 19,000 kw. capacity, situated about two miles away.

The automatic station contains three 500 k.v.a., 2300 volt, two-phase, 60-cycle generators, driven by Francis-type water-wheels running at 60 r.p.m., under a head of 10 ft. Normally the starting and shutting down of these sets is accomplished automatically through the medium of float switches, affected by the rise and fall of the level of water above the dam. Provision is made, however, so that these operations, as well as the individual gate openings, can be controlled by push buttons in the main power house. Here there are also installed a full set of instruments enabling the working of the automatic station to be watched. To this end, 54 control conductors are run between the two stations, in addition to the main power conductors from the automatic station bus-bars.

The various steps in the operation of starting and stopping are effected by means of a motor-driven controller, and a series of industrial-type contactors. For full details of the means adopted, and diagram of connections, reference should be made to the paper by Messrs. J. M. Drabelle and L. B. Bonnett, " The Automatic Hydro-electric Plant ", *Trans. American I. E. E.*, 1918, Vol. XXXVII, Part II, page 1367.

Here it may be summarized that the closing of either a float switch or the corresponding push button in the main steam generating station results in the following sequence:

1. Motor-driven controller starts.
2. Motor-driven exciter set starts.
3. Gate is opened to a limited extent.
4. Motor-driven controller stops till generator reaches speed, when it is re-started.
5. Generator without field is connected through reactances to bus-bars which are permanently tied into the main system.
6. Weak field applied to generator, allowing it to be pulled into synchronism by the main station.
7. Field increased to normal.
8. Reactance short-circuited.
9. Gate opened farther till generator carries normal full-load current.

The whole of this process ocupies less than one minute.

When starting up from a standstill, energy for the servo-motors may be drawn through transformers from the main station. If there is power on the bus-bars of the automatic station, the transformers are connected thereto, change over from one source of supply to the other being effected automatically.

When a float switch opens, or the shut-down push button in the main station is closed, all conductors controlling the generator concerned are opened and the motor-driven controller returns to the start position. The exciter is not affected, however, unless this be the only generator operating.

There are two exciter sets, each driven by a 2300-volt induction motor, either being large enough to excite all the generators. A double-throw hand switch is provided so that either one or the other will be started automatically with the first generator to be put on load.

The provisions for ensuring safe operation when running are of considerable interest. The gate movement is controlled by a contact-making ammeter, which, through suitable contactors, reverses the motor and closes the gate should the current exceed a certain amount. If the excessive current is due to trouble in the generator winding, an overload inverse time-limit relay should operate to open the generator contactor as well as the exciter motor circuit. The generator and exciter are similarly shut down should the frequency exceed 64 cycles, or should the exciter voltage fall below a certain limit.

In the event of failure of A.C. voltage, all contactor magnets would lose

their supply and drop out, leaving the controller motor so connected that as soon as pressure is restored, it turns the controller round to the start position.

Thermostats are provided on the machine bearings, these operating to shut down the sets in the event of overheating, in the same manner as the overload relays.

Should a " stop " button in the main station be pushed, the first contactor to open takes control, so that even though a " start " button be pressed immediately afterwards, the automatic devices in the station must go through the whole sequence of operations for starting up. In this way any chance of a running machine being momentarily disconnected and then thrown in out of step is avoided.

Such a plant as this is, after all, only an elaboration of the automatic rotary converter sub-stations, now widely used in America. These in their turn were merely new applications for the contactor type of control gear which had been working in industrial fields with the greatest success for some years past. The components are consequently well-tried pieces of apparatus, and the problem becomes more one of interlocking and adjustment. In the early stages, a considerable amount of care and adjustment was doubtless necessary, and at all times periodical inspection of automatic devices and contacts is essential.

The automatic generating station appears eminently suited to systems where numerous small-power falls are available. In such a case the expense of an operating staff at each place would be prohibitive, but if each station can be made automatic, and all linked on to a common distribution system, the labour cost can be reduced to a minimum. This might easily make possible a development which would be unable to pay a reasonable return on investment, were stations requiring full supervision to be installed.

Future generating stations along these lines may well be expected to be simpler, but also more adequately protected. For instance, the alternative control from a distance will heavily burden a project if for each generator some nine or a dozen control leads must be run, as in this case. It will be necessary either to dispense with some of the remote control features, such as indicating instruments at the central point and remote gate control gear, or else find a new and simpler means for effecting control.

Central control would be highly desirable in places where several small automatic stations are situated on the course of the same stream or river in order to ensure that the water is used to best advantage at all points. Without means for shutting down certain plants from a distance, it would be necessary for an operator to be more or less constantly between the plants to perform this duty.

It has been pointed out that the automatic generating station is a development of the automatic rotary converter sub-station. Main control of the latter is effected in one of two ways, either by a motor-driven controller (as in the Iowa generating station), or else by a suitable sequence of relays. The relay scheme has much in its favour, since the actual conditions prevail-

ing with each machine controlled determine the movement of the starting devices. The motor-operated controller moves forward more or less " blindly ", once it is started. The relative lengths of the contact segments are based on the time necessary to perform each step in the starting operations. If anything stalls the motor will still pass on to the next step. If sequence relays are used, the stalling of a machine would cause a stop, either until the machine had got away, or until the trouble was repaired.

A further advantage, which, however, is only of secondary importance in a generating station, is that the relay scheme gives a quicker start if everything is in good order, since the segments on a controller must of necessity be long enough to allow a start under bad conditions. The longest time thus becomes the *only* time of start with the motor-driven controller scheme.

The automatic protection for each generator should be that desirable in a conventional power station, i.e. balanced current relays in conjunction with a field killing device, and these should operate to shut down only that section of the plant affected. Thermostats, over-speed trips, and direct-current low-voltage relays should be employed in addition, in a manner similar to that described above.

In the case of the Iowa plant, operation is considerably simplified by reason of the large steam station with which it is connected, since the latter will control both voltage and frequency, making special automatic arrangements in the small station unnecessary.

In the majority of cases this condition cannot be expected to hold. Arrangements must therefore be made to apply voltage regulators to the generators, these regulators being cut out of circuit until the machine is on full field and the synchronizing reactances short-circuited.

Frequency control is of considerable importance in any system where power is used for industrial purposes, since the speed of motors, and hence of driven machinery and its manufactured output, varies directly with the frequency. The type of speed-limit device used in the Iowa station is not sufficiently sensitive to be worked independently, neither can the ordinary hydraulic turbine governor be depended upon to keep speed within say ± 1 per cent at all loads. At least one American manufacturing concern has developed an electrical instrument to operate within this range, to keep the frequency commercially constant.

Since the above was written, two other automatic plants have been started up. In these remote control is dispensed with, and relay starting adopted. Further installations of this type are pending.

5. The Thury System.—Although it has found only a very limited application in practice, some attention must be given to the Thury system of generation and transmission with high voltage direct current. With this system all generators and motors are in series, the current remains constant, and the voltage is varied according to the power demand. It can thus be considered as an elaboration on the earliest methods of distributing D.C. for arc lighting. The Thury system was, in fact, developed before alternating-current transmission was practicable.

At the outset it must be recognized that the system possesses certain advantages from the point of view of transmission, but it is totally unsuitable as a system for the distribution of energy. Motors must be designed to take a constant current at a voltage varying according to the horse-power. In most cases this will involve insulation for a much higher pressure than is usual on D.C. motors, with the attendant elaboration of commutator design. Although the pressure across terminals will not exceed the practical limits for winding insulation, the voltage above earth may be far greater, and consequently every motor frame has to be insulated from earth.

Every motor used on this system requires a governor to prevent the speed varying with the load. Such machines are not included in the standard lines of manufacture, and would have to be built specially in each case. The first cost is naturally much higher than that of a motor used on the usual A.C. or D.C. systems.

In practice Thury transmission lines always terminate in a sub-station in which the energy is transformed in rotating machinery either to D.C. or A.C. for constant voltage distribution.

Considered solely as a means for transmitting energy in bulk from one point to another, the Thury system has usually been found more expensive than high-voltage A.C. The most important installations are those of the Société de Force et Lumière of Lyons, France, the Metropolitan Electric Supply Company in London, and the transmission by submarine cable from Trollhätten, Sweden, to Copenhagen in Denmark.

In principle the system is extremely simple. All generators are series wound and connected in series, electrical control of each being by means of a rotary switch to short-circuit the machine when not required. As the line current must be maintained constant, each generator has a governor which either varies the speed of prime mover, or, if the speed of the latter must be constant, shifts the brush rockers. The former method is the more usual.

Accuracy of speed governing is of no great importance as the machines will properly subdivide the load even with difference of speed as much as 10 per cent. When starting up the valve is opened with the generator short-circuited. As soon as it has built up to normal current the rotary switch is moved so as to remove the short-circuit and introduce the generator in series with the system.

This latitude in operating conditions, coupled with the entire ease with which a generator is put in service, makes the system very suitable for cases where many small sources of power are required to serve a common transmission system.

The maximum voltage per commutator so far constructed is 5000. The system pressure may be as high as 80,000 or 100,000 volts, thus giving a very large number of generating units. As stated previously all generator frames are insulated, and it is usual to surround the machine with a wide insulated platform to ensure safety for the operators.

The principal advantage of this system would appear to lie in the absence

of capacity and induction effects. This alone may make a careful study desirable in future cases where much higher A.C. voltages than now used seem to be essential.

Suitable cables for high-voltage D.C. have been constructed for pressures of 70,000 to 80,000 volts, and these have been in use for a sufficient term of years to prove their entire reliability. When the point of consumption is in a city area, as is usually the case, it is a great advantage to be able to bring high-voltage cables right in, instead of being forced to erect a transformer sub-station on the outskirts of the city.

As rotating machinery is always required at the terminals of a line, no added difficulty is found when using the Thury system to tie between A.C. stations of various voltages and frequencies. It was largely for this reason that Mr. J. S. Highfield advocated its employment to tie together the many power plants in London.

Sufficient has been said to indicate that while in the vast majority of cases distribution at high voltage A.C. is the more advantageous, special conditions may arise which will warrant the investigation of a system employing high-voltage direct current.

CHAPTER XII

Economics of Hydro-electric Development

Primary and secondary power; diversity factor; electro-chemical load; cost of hydro-electric power; Swedish powers; cost of fuel power; limiting cost of hydro-electric plants; steam auxiliary plants; actual cost of hydro-electric plants; cost of transmission; costs to consumer.

1. Possibility of Economic Development.—The possibility of the economic development of a hydro-electric scheme depends essentially upon:

(*a*) whether there exists, or is likely to exist, a market for the power;
(*b*) whether the price at which the power can profitably be sold is, firstly, such as the industry can afford to pay, and secondly, less or at least not greater than the price of power from a fuel-operated station.

Without some definite guarantee of a market for the power, no power scheme can be considered as an economic proposition. It is true that experience has shown that in industrial countries industries will tend to gravitate towards a centre where cheap power is available, but this is not to be accepted as a truism without qualification. If power can be developed sufficiently cheaply, if raw material is available near to the site or can be transported there cheaply, and if satisfactory transportation facilities are available, this is generally true of those industries utilizing electro-chemical or electro-physical processes requiring a large amount of power, and whose capital charges and labour charges are relatively small. On the other hand, such industries are in general economically incapable of paying a high price for power, and may be ruled out as possible consumers unless the water power can be very cheaply developed, or unless they can be brought in to increase the load factor or to enable water to be utilized which would otherwise be wasted.

Under normal conditions, in an existing industrial community a market for the full capacity of the plant can only be created gradually. Factories already operating on a fuel-power plant must either dispose of such plant, usually at a sacrifice, or must keep it standing idle, and must in addition expend capital in electric motors. Moreover, it is seldom that the average steam-power user estimates the cost of producing his existing power at nearly its true value, and the price at which electric power can be offered to such potential consumers must be very low in order to make the change-over

appear attractive to them. In such a case a careful survey of the district is necessary to determine the extent of the probable power demand.

Even with a potential market in existence, if the cost of hydro-electric power appreciably exceeds that of steam-generated power, no economic development is possible, and even if the power is cheaper than steam power it may still cost more than the only possible industry can afford to pay.

Much also depends upon the type of load, and especially upon the load factor (see Arts. 7–10), and a hydro-electric installation which is economically unsound if developed to supply a continuous load in competition with a steam station, may prove to be sound if developed to supply an ordinary industrial load with a load factor of 30 to 40 per cent.

2. Primary and Secondary Power.—A study of the hydrograph of any normal river shows that the power available at a given site varies greatly from month to month. Where the flow is not regulated by storage works, the maximum output which can be maintained continuously depends upon the flow available after a long period of drought. This is appreciably less than the minimum dry-weather flow during an average year. On the other hand, during the wet months, much more power is available, except where flood conditions necessitate a partial shut-down. On any normal unregulated river a hydro-electric installation may be designed either:

(*a*) to utilize only the amount of minimum dry-weather flow;
(*b*) to utilize the average dry-weather flow;
(*c*) to utilize appreciably more than the average dry-weather flow.

If system (*b*) or (*c*) be adopted, and if the output guaranteed to consumers exceeds that possible during the worst period of drought, it becomes necessary to install fuel-operated auxiliary generating machinery. The expenditure on this plant is to be debited to the cost of the development. It may be appreciably reduced by disregarding high fuel economy, since the saving of interest on first cost and other fixed charges will usually far outweigh the cost of the excess fuel consumed during its restricted period of operation.

The necessity for such auxiliary power may, however, be avoided or reduced if contracts can be made with consumers to take intermittent power at a reduced rate. Under such circumstances three classes of power contract may be made:

These refer to:

(*a*) a guaranteed constant supply;
(*b*) a supply subject to withdrawal only during long periods of drought, or during excessive floods;
(*c*) a supply given only during the wet season, which will usually include at least six months of the year, and may include eight or nine months.

The relative market value of these classes of power depends largely upon the special circumstances, but may be taken roughly on the ratio of 3 : 2 : 1.

The possibility of obtaining contracts for such secondary power will

evidently influence the design of the installation. The amount which can profitably be developed depends upon the characteristics of the stream flow, on the selling price of the current, and on the cost of the additional constructional work and equipment which it involves. While each case must be considered on its own merits, it may be taken very roughly, except where the head is greatly affected by flooding, that the maximum power which can be developed continuously for x months in each year from a normal stream in a temperate climate, without storage, is given by

$$A + \frac{B(12 - x)}{11\sqrt{x}},$$

where A is the horse-power output during the period of minimum flow; where x is the number of months (from 1 to 12); where A + B is the maximum possible output in horse-power throughout the wettest month, or that month giving maximum output.

If the capital cost to be charged to that portion of the scheme rendered essential to develop the secondary power is £C per horse-power, the capital cost corresponding to full output of secondary power for x months per annum is £$\frac{BC(12 - x)}{11\sqrt{x}}$, and the cost of producing this power, reckoned at w per cent of the capital cost will be £$\frac{w\,BC(12 - x)}{1100\sqrt{x}}$ per annum. If the sale price is £Px per horse-power year, the profit p on this portion of the outlay will be

$$£\left[\frac{PB(12 - x)\sqrt{x}}{11} - \frac{w\,BC(12 - x)}{1100\sqrt{x}}\right].$$

For maximum profit $\frac{dp}{dx} = 0$, which leads to the result

$$x = \left(2 + \frac{w\,C}{600\,P}\right) + \sqrt{\left(2 + \frac{w\,C}{600\,P}\right)^2 + \frac{4\,w\,C}{100\,P}}$$

as the condition to be satisfied. Thus if $w = 9{\cdot}5$ (p. 259) and if P = £0·33 and C = £15, $x = 7{\cdot}7$, and for maximum profit the installation should be designed to utilize the maximum power which can be developed continuously for 7·7 months in each year. Similarly, if P = £0·33 and C = £25, or if P = £0·20 and C = £15, the value of x becomes 2·5 months, while if P = £0·33 and C = £42, the value of x would be 12 months, indicating that in this case the most economical scheme would only attempt to develop up to the minimum flow capacity of the stream.

Where, by the addition of auxiliary steam or gas plant, the continuous output of what would otherwise be secondary power can be guaranteed, this becomes primary power and its market value is correspondingly increased. When the market value of the power and the cost of generation per horse-power of the necessary steam power is known, the capacity of the steam

plant for maximum profitable operation may be determined as in the foregoing case.

3. **Diversity Factor.**—In a plant supplying an ordinary industrial load, the sum of the capacities of the consumer's motors may, normally, be much greater than the rated capacity of the power plant, since these motors will never all be operating at full capacity at any one time. Moreover, a water-power plant always has a certain capacity for overload for short periods, which will enable any unusual demand to be met.

The value of the " diversity factor ", or the ratio of the maximum capacity of the motors installed to that of the generating plant, varies largely with the type of load. In ordinary industrial plants it varies from about 1·25 to 2·4 with a mean value of about 1·6. A careful examination of the general conditions likely to exist in the locality to be supplied is necessary to determine what diversity factor may reasonably be allowed. In general the larger the number of consumers, and the smaller the size of the individual motors, the greater may be the excess motor capacity contracted for. Moreover, since the cost of power generation from fuel-operated plants is greater for small than for large powers, a higher charge can reasonably be made for power supplied in small units. It is therefore desirable from almost every point of view to supply as many customers in small units as possible.

Economically a lighting load is valuable, since the extra expense which it involves is small compared with the income which it brings. Where a hydro-electric scheme is largely independent of storage, any night load is of great advantage, since the only charge to be debited against it is that of the extra attendance and supplies required. In consequence the income derived from its sale is almost all profit.

4. **Possibilities of Electro-chemical Load.**—The many electro-chemical processes which are now in use for the manufacture of such materials as aluminium, carbide, cyanamide, carborundum, bleaching powder, caustic soda, and nitrates for artificial fertilizers, are dependent for their commercial success on an ample supply of cheap electrical energy, and it is only, in general, by hydro-electric development that energy can be supplied at the necessary low cost. Such processes are as yet in their infancy, and it is impossible to predict the effect of their ultimate development. Of the total water developed in France and in Norway, approximately 50 per cent, and in Sweden some 33 per cent, is now absorbed in their operation.

The majority of such processes demands that the manufacture be carried out in close proximity to the water-power site, firstly because they require direct current at low voltage which cannot be transmitted for large distances without prohibitive cost, and also because, even with high-tension alternating transmission, the additional cost per unit delivered, due to the cost of a long transmission line and to the losses in transformation and transmission, will usually render the total cost too great for such purposes. Under favourable conditions, with the factory at the water-power site, the market price of several of the products is such, however, that they are able

to stand a considerable cost of freightage, and may be manufactured at a long distance from their natural market. Among such products aluminium requires the largest amount of energy per pound of output, this amounting to approximately 12·5 kw. hours per pound, or 3·2 kw. per annum per ton, and aluminium is consequently very dependent on the low cost of power. Owing to its relatively high value per pound, aluminium factories may be installed at a considerable distance from the centre of gravity of distribution if energy can be obtained at a cost in the neighbourhood of £4 or £5 per kilowatt year of continuous power. Artificial abrasives have an energy consumption of about 1·5 kw. per annum per ton, but owing to the price of the finished product such factories, with power at the above price, cannot stand much more than one-half the freightage allowable for aluminium. Calcium carbide requires from 0·66 to 1·0 kw. per annum per ton. Carbide, ferro alloys, and chlorates are in much the same position as artificial abrasives as regards the economical limit of freightage. Pig-iron smelting requires from 0·23 to 0·26 kw. per annum per ton, and steel furnace operation offers a profitable outlet for power, even at the end of a long transmission line.

In general the use of daily off-peak power is not suitable for electro-chemical processes, owing to the increased overhead charges, and to the necessity for keeping the furnaces hot for periods exceeding those for which the power is available, and it would appear that unless a load factor of at least 80 per cent can be maintained, such processes are not commercially feasible under normal conditions. Secondary power, available only for six to nine months per annum, is not economically attractive to the average electro-chemical industry.

5. Cost of Hydro-electric Power.—Capital charges account for the greater part of the cost of energy from the average hydro-electric scheme. The capital cost includes all expenditure due to:

1. Preliminary investigations, promotion, and organization.
2. Land and water rights, and rights of way for transmission lines, &c.
3. All constructional work, including the engineer's fee for designing and supervising the plant, and the salaries of any officials receiving pay during the constructional stage.
4. Interest on all money expended up to the stage where the plant is completed and delivering power to the consumers.

The interest charges on this capital, together with the other fixed charges such as insurance, rates and taxes, and sinking fund, usually form about two-thirds of the total costs of the power, and are independent of the output. The other items of expense—administration, labour, supplies, repairs, and depreciation—vary somewhat with the output, but not nearly so much as in a steam-power plant. In general it may be taken that the total costs per unit of output of a hydro-electric plant vary almost inversely as the output, and for this reason the provision of a market for the full capacity of such a plant is of great importance.

6. Operating Expenses.—The operating expenses comprise:

1. Wages and salaries.
2. Supplies.
3. Repairs and maintenance.
4. Depreciation.

In general an allowance of 0·5 per cent on the capital cost of the hydraulic works and buildings, and of 1·5 per cent on the capital cost of the machinery and transmission lines, is adequate for their repair and maintenance.

Depreciation forms the most important single item of the operating expenses, and is the one which is most frequently overlooked or inadequately recognized. The depreciation fund should be set aside annually, and should be adequate to provide for the replacement of any part of the equipment which may be worn out or become obsolete. It should also be sufficient to cover any additions or improvements which may be necessary to meet increased competition, or some change in operating conditions, where such extra expense does not result in an increased net profit. The proper amount of this fund will depend on the special conditions of each plant. Under normal conditions, however, the following percentages on the first cost of the various items of the installation have been found adequate.

		Per cent.
Civil engineering works, including dams, conduits, headworks, power house, &c.		1·5
Pipe lines and sluice gates		2·5
Electric generators, transformers, and switch-gear		4
Hydraulic turbines and governors		4·5
Transmission lines	towers	3
	cables	5
	insulators	10
Operating machinery in power house, cranes, hoists, &c.		5

In the majority of cases the annual depreciation charges, expressed as a percentage of the total constructional costs, lie between $2\frac{1}{4}$ per cent and $3\frac{1}{2}$ per cent, depending upon the relative costs of the civil and of the mechanical and electrical engineering portions of the work.

Valuable information is available, regarding capital and operating costs, from a recent report, by the Swedish Government, on the *Developed Water Powers of Sweden*. In these installations fuel-power plant is used as a reserve to the extent of 10 per cent of the total power installed. Of the total number of installations 78·5 per cent, representing a capacity of 171,500 h.p., or 15·6 per cent of the total output, are of less than 1000 h.p. There are 27 undertakings of 5000 h.p. or over, which account for 58·6 of the total output. The load factor varies from a minimum of 28 per cent to a maximum of 55 per cent, with a mean value of about 42 per cent.

Taking the kroner as equivalent to 13·5 pence, the average capital cost of the water-power works, including fuel plant in reserve, but excluding transmission machinery, is £11·7 per turbine horse-power, or £13·7 per horse-power of total capacity including fuel plant.

The effect of an increase in the size of the plant, and in the working head, upon the capital cost per turbine horse-power installed, is shown by the curves of figs. 1 and 2.

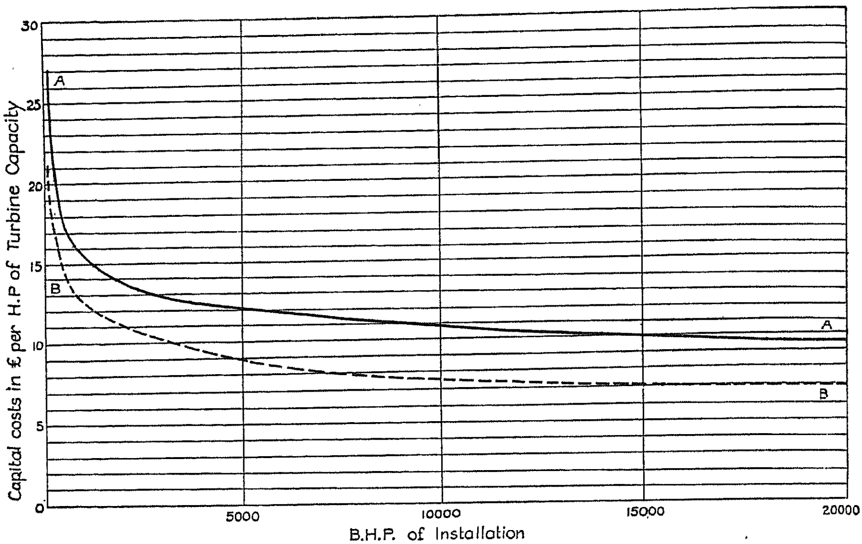


Fig. 1.—Effect of Size of Plant on Capital Cost

Taking the case of electricity undertakings, constructional work accounts, on the average, for about 75 per cent, and machinery for 25 per cent of the capital expenditure. Of the expenditure on machinery, the turbines and

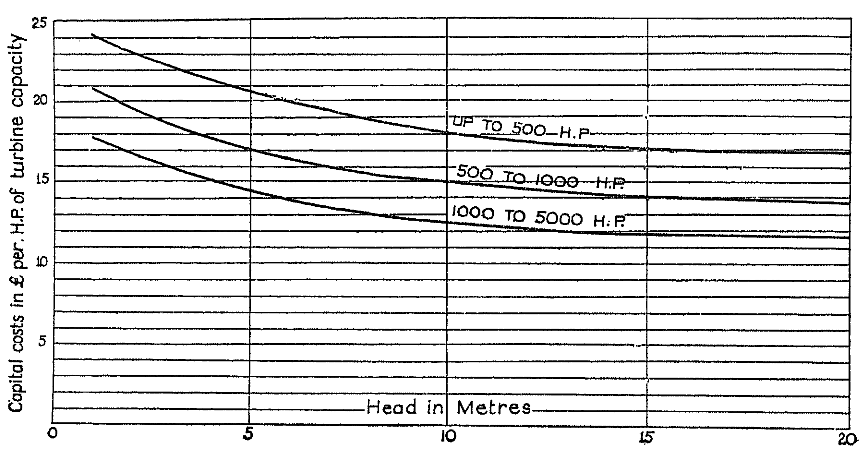


Fig. 2.—Effect of Working Head on Capital Cost

accessories account for about 33 per cent, and the electrical equipment for 67 per cent.

The annual running costs, excluding depreciation, average slightly over

12*s*. per turbine horse-power installed. These average costs per horse-power are as follows:

	Shillings
Administration	1·91
Staff for machines	2·44
Staff for distribution	0·72
Oil and stores	0·59
Fuel	2·06
Repairs and maintenance	1·98
Water rights and rent	0·27
Insurance	0·21
Rates and taxes	0·79
Other incidentals	1·18
Total	12·15

Excluding fuel and the wages of the staff engaged on distribution, this becomes 9·37 shillings per horse-power.

There is, however, a large variation in the working costs in the different

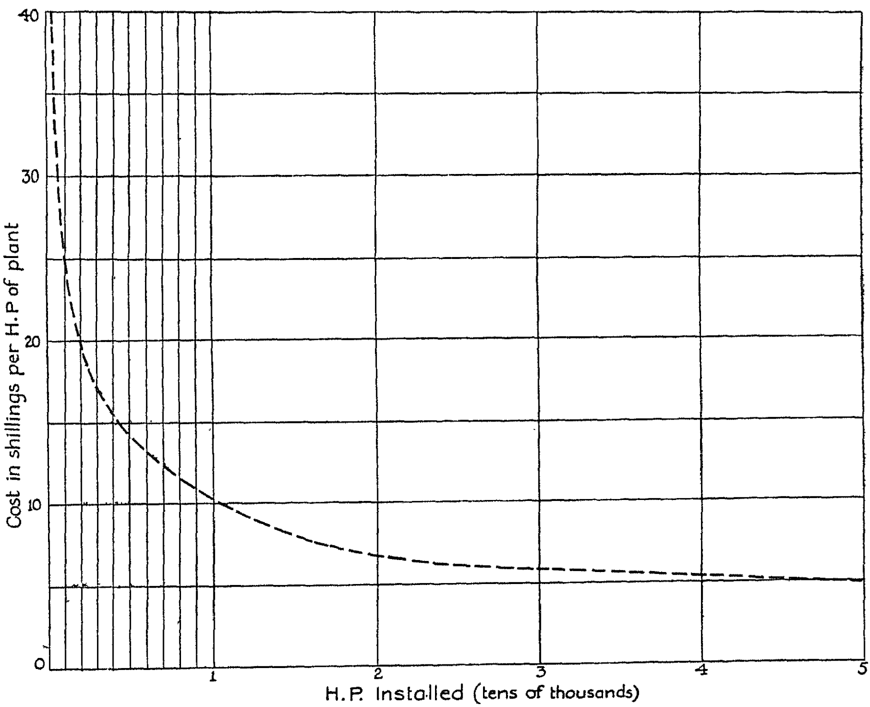


Fig. 3.—Effect of Size of Installation on Running Costs per Horse-power

classes of undertaking. Thus the average working costs, including fuel and distribution, at communal undertakings engaged in general distribution, amount to approximately 0·3 pence per kilowatt hour, while the corresponding average costs at industrial undertakings of 5000 h.p. and upwards are only about 0·02 pence per kilowatt hour. The general effect of the size of installation on the running costs is shown by the curve of fig. 3.

In estimating the total cost of power from these installations interest has been taken at 6 per cent; thirty years have been allowed for writing off the costs of buildings and hydraulic works, corresponding to a depreciation fund of 1·3 per cent; and fifteen years for machinery and transmission lines, corresponding to 4·3 per cent. For maintenance 0·5 per cent is allowed for buildings, and 1·5 for machinery and transmission lines. From the results it appears that the total cost of power may be taken as made up of:

1. A percentage charge varying from 3·0 to 3·3 per cent on the capital outlay for construction and machinery, to cover repairs, maintenance, and depreciation.
2. Interest upon the total capital outlay.
3. An annual charge per turbine horse-power or per kilowatt installed, to cover all other working costs. This charge varies appreciably with the size and type of installation. Expressed as a percentage of the capital costs of construction, its value is as follows:

Private distribution	Per cent.	*Industrial for works requirements*	Per cent.
Up to 100 h.p. ..	6·2	Up to 1000 h.p. ..	4·4
1000 to 5000 h.p. ..	4·5	1000 to 5000 h.p. ..	2·6
5000 and over ..	3·2	Over 5000	1·8

Communal	Per cent
General distribution	4·7
Industrial distribution	3·3

From these results it appears that the total annual cost of power, in an installation of 5000 h.p. or upwards, averages approximately 11 per cent of the capital cost where no extensive transmission and distribution is involved, and about 12·5 per cent of the capital cost in a system involving transmission.

Owing to the relative cheapness of construction of the majority of the Swedish water powers, the annual costs, expressed as a percentage of the capital cost, are likely to be somewhat higher than in the average more costly installation. In the case of one electro-chemical plant in the United Kingdom, of a capacity of 20,000 kw. and operating on a load factor of 87 per cent, the working costs per kilowatt year of output, exclusive of interest on capital, amount to 3·2 per cent on the capital cost per kilowatt installed, or 2·75 per cent of the capital cost per effective kilowatt. In this case depreciation represents an annual charge of 2·24 per cent, and labour and other working expenses a charge of 0·51 per cent. The capital cost per kilowatt installed is approximately £31.

In the case of another small installation of 635 kw., installed on an existing weir and without storage, and operating on a load factor of 29 per cent, the average annual working costs, inclusive of interest and sinking fund charges at 6·8 per cent, amount to 9·6 per cent of the total capital cost. This capital cost is approximately £24 per kilowatt installed.

An examination of a number of typical Canadian, American, and European installations indicates that the total annual costs, excluding transmission,

and taking 6 per cent as the rate of interest on capital, amount very nearly to 9·5 per cent of the capital cost. This figure appears to apply very approximately whether the load factor be low or high, and may be taken, without any great error in estimating the probable cost of power, or as a basis of comparison in estimating the limit of economical expenditure of a hydro-electric plant to compete with a fuel-operated plant. Where transmission over a moderate distance, say 30 to 60 miles, is necessary, the appropriate figure is approximately 11·0 per cent of the capital cost inclusive of transmission lines and terminal station.

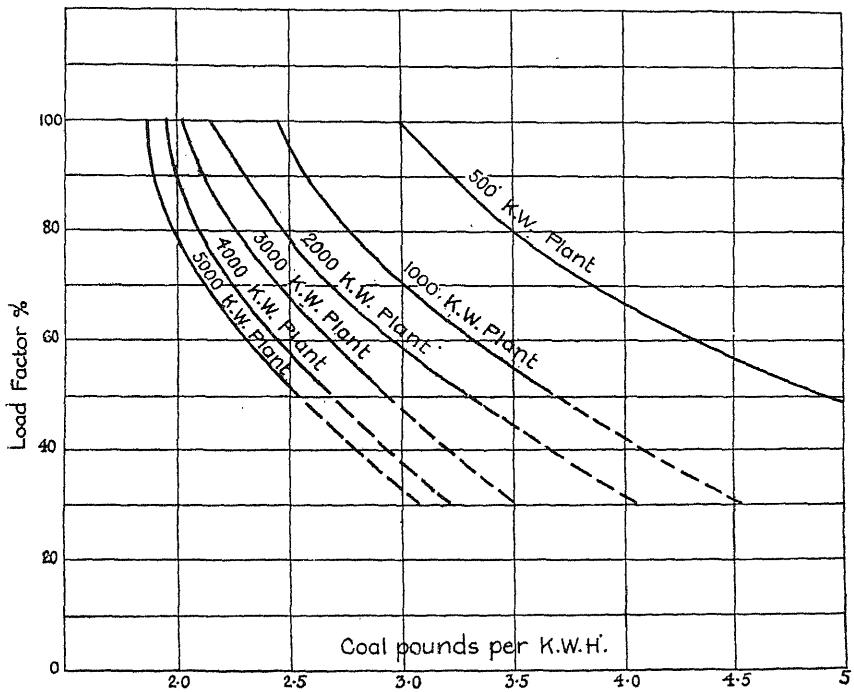


Fig. 4.—Effect of Load Factor on Coal Consumption of Steam Plants

7. Cost of Power from Fuel-operated Stations.—The cost of power from fuel-operated stations depends largely upon the type of machinery installed, the size of the units, the load factor, and on the efficient operation of the plant. The latter factor is of more vital importance than in a hydro-electric installation, and experience shows that the fuel consumption per unit of output in two installations having identical plant may readily vary by as much as 30 or 40 per cent.

Steam plant.—The general effect of a change in the load factor on the fuel consumption of steam plants is shown by the curves of fig. 4,* while the following table,* which shows the average coal consumptions from 73

* *Report on the Rate of Coal Consumption in Electric Generating Stations and Industrial Establishments in Canada and the United States.* Hydro-Electric Power Commission of Ontario, Toronto, February, 1918.

representative steam-electric generating stations and industrial establishments in the United States of America and Canada during the past five years, indicates how the coal consumption varies with the size of plant.

Station Capacity, Kilowatts.	Tons (2240 lb.) per Kilowatt Year, at 35 per cent load factor.
Over 100,000	2·94
50,000 to 100,000	3·08
10,000 to 50,000	4·38
5000 to 10,000	6·25
1000 to 5000	6·58
Under 1000	11·80

An investigation of the pre-war costs of between 40 and 50 steam generating stations in the United Kingdom, having a capacity of 4000 kw. or over, shows that the capital cost including land and buildings, railway sidings and wharfs, but excluding all transmission and distributing machinery, varies from about £17 to £45 per kilowatt of maximum capacity. A smooth curve drawn through the plotted points gives the following average capital costs, which are, however, subject to wide variations.

Maximum Capacity, Kilowatts.	4000.	10,000.	20,000.	30,000.	40,000.
Capital cost per kilowatt	£30	£26·5	£22·5	£19·0	£17·5
Coal, tons per kilowatt year: 30–40 per cent load factor	5·4	4·8	4·0	3·7	3·5
Coal, tons per kilowatt year: 95 ,, ,,	9·8	8·4	7·1	6·3	6·0

The average pre-war costs of generation, exclusive of coal and capital charges, but including repairs and maintenance, supplies, salaries, and wages, are equivalent, with a load factor of 30 to 40 per cent, to an approximate charge of 3·5 per cent, and with a load factor of 95 per cent (continuous output) would be equivalent to an approximate charge of 6·5 per cent upon the capital cost per kilowatt of maximum load. The average coal consumption in tons per kilowatt year at the actual load factor involved is given in lines three and four of the foregoing table. The figures for continuous output have been deduced from the measured figures at the actual load factor of 30 to 40 per cent, from the data of the curves of fig. 4, and to this extent are tentative.

Taking interest charges as equivalent to 6 per cent of the capital cost, and allowing an over-all charge of 4 per cent for depreciation and sinking fund in the case of a 30 to 40 per cent load factor, and of 5 per cent in the case of a 95 per cent load factor, the total costs of power, at the switch-board of the power station, with coal at 10*s*., 15*s*., and 20*s*. per ton, are as given in the following table.

Cost per Kilowatt Year of Output at given Load Factor.							
Maximum Capacity, Kilowatts.			4000.	10,000.	20,000.	30,000.	40,000.
			£	£	£	£	£
Load factor 35 per cent.	Interest and sinking fund ..		1·80	1·59	1·32	1·13	1·05
	Depreciation		1·43	1·06	0·88	0·76	0·70
	Repairs, maintenance, supplies, salaries, and wages ..		1·05	0·93	0·77	0·66	0·61
	Coal	at 10*s*. per ton	2·70	2·40	2·00	1·85	1·75
		at 15*s*. ,, ...	4·05	3·60	3·00	2·77	2·62
		at 20*s*. ,, ...	5·40	4·08	4·00	3·70	3·50
	Total costs	at 10*s*. per ton ..	6·97	5·98	4·97	4·40	4·11
		at 15*s*. ,, ..	8·32	7·18	5·97	5·32	4·98
		at 20*s*. ,, ...	9·67	8·38	6·97	6·25	5·86
Load factor 95 per cent.	Interest and sinking fund ..		1·80	1·59	1·32	1·13	1·05
	Depreciation		1·50	1·33	1·10	0·95	0·88
	Repairs, maintenance, supplies, salaries, and wages ..		1·95	1·72	1·43	1·23	1·14
	Coal	at 10*s*. per ton	4·90	4·20	3·55	3·15	3·00
		at 15*s*. ,, ...	7·35	6·30	5·32	4·72	4·50
		at 20*s*. ,, ...	9·80	8·40	7·10	6·30	6·00
	Total costs	at 10*s*. per ton ..	10·15	8·84	7·40	6·46	6·07
		at 15*s*. ,, ..	12·60	10·94	9·17	8·03	7·57
		at 20*s*. ,, ..	15·05	13·04	10·95	9·61	9·07

The following estimates have been extracted from the final report of the Nitrogen Products Committee of the Board of Trade. They are based upon the latest pre-war figures, and give the capital and operating costs of two steam-electric stations, one having an installed capacity of 125,000 kw. and a maximum load of 100,000 kw., and the other an installed capacity of 6250 kw. and a maximum load of 5000 kw. The figures for a load factor of 95 per cent are:

	Costs, £, per Kilowatt Year.	
	100,000 kw.	5000 kw.
Salaries and wages	0·14	1·00
Oil, stores, and sundries	0·10	0·20
Repairs and maintenance	0·30	0·50
Coal at 10*s*. per ton	2·97	3·97
Capital charges— 4½ per cent on capital .. .. 2½ per cent depreciation on buildings 5 per cent depreciation on machinery	0·91	1·73
Total	4·42	7·40

Modifying these figures to allow for a charge of 6 per cent for interest, and

making an approximate allowance for the differences in fuel consumption, stores, and salaries, during operation at 35 per cent load factor, these total costs become:

	Cost per Kilowatt Year.	
	£	£
Load factor, 95 per cent — Coal at 10s. per ton ..	4·60	7·83
,, ,, 15s. ,, ,, ..	6·06	9·80
,, ,, 20s. ,, ,, ..	7·53	11·76
Load factor, 35 per cent — Coal at 10s. per ton ..	3·10	5·28
,, ,, 15s. ,, ,, ..	3·95	6·36
,, ,, 20s. ,, ,, ..	4·80	7·45

These costs are on the average about 25 per cent lower than those deduced from the records of existing stations (p. 261), and represent more nearly the

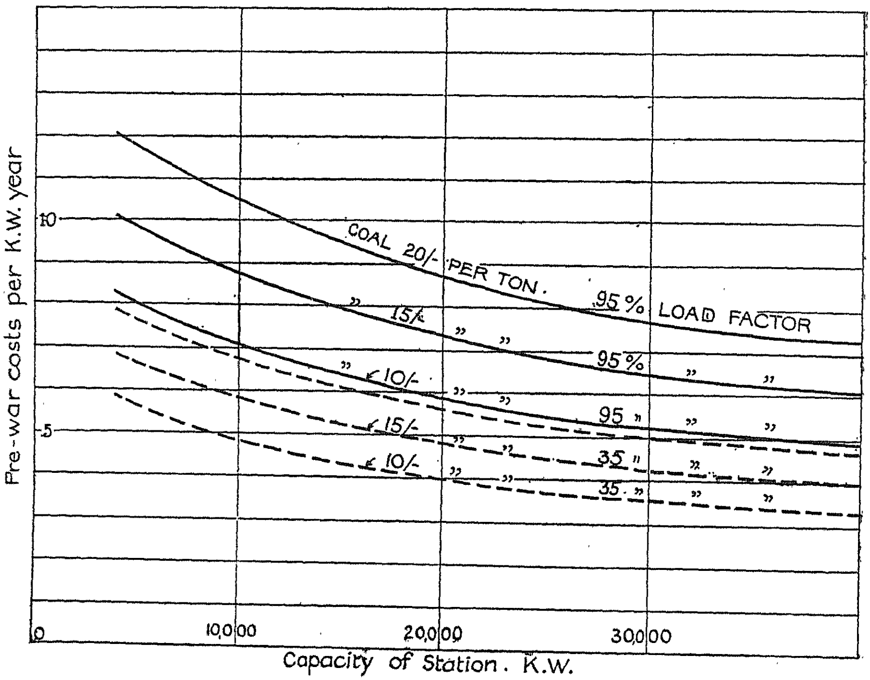


Fig. 5.—Over-all Costs of Steam Power

pre-war costs at the best modern and well-designed generating stations. The curves of fig. 5, which represent the figures of the table on p. 261 reduced by 25 per cent, may be taken as giving, with a fair degree of accuracy, the minimum average costs of steam-generated electric energy with coal at 15s. per ton, from such stations.

It will be noted that in all the foregoing estimates of cost, interest has been taken at 6 per cent, i.e. at post-war rather than pre-war rates. With interest at $4\frac{1}{2}$ per cent these total costs would be reduced by approximately 8 per cent.

In using the data of these curves as a basis for comparing the cost of power generated from a steam station with that of hydro-electric power, it is to be remembered that they refer to complete generating stations, and that the cost of land, roads, railway sidings, and all buildings is debited to the power account. In the case of an industrial factory having its own steam plant, the proportion of these items of cost to be debited to the power house is very small, and the capital charges are consequently smaller, as also is the cost of administration. Moreover, the foregoing values also include the cost of electric generators, switch-gear, and transformers, which are absent in the case of a factory with direct driving on to the line shafting, and in such a case the capital charges will be little more than one-half those given above. On the other hand the size of unit for the average factory is small and the coal consumption, as indicated by the curves of fig. 4, is relatively high, so that the over-all charges per unit of power developed will not be very different from those of the larger electrically equipped installations.

When it is a case of comparing the costs of power from a new hydro-electric station and from a new large steam station, the data of fig. 5, with an appropriate allowance for the difference between pre-war and post-war costs, may be taken as an approximate basis of comparison. While it is impossible to give any definite relation between pre-war and post-war costs, assuming the latter constructional costs, as also the costs of supplies and wages and salaries, ultimately to become stabilized at approximately 1·5 times the former, if the post-war cost of coal be taken at 22·5*s.* per ton, the over-all costs will be 1·5 times those indicated by the curve of fig. 5 for coal at 15*s.* per ton, while if the multiplying factor be taken as 2·0, and the post-war price of coal be taken as 30*s.* per ton, the over-all costs will be twice those indicated by this curve.

Gas-engine Electric Stations.—The following figures for the capital and operating costs (pre-war) of a gas-engine electric station having an installed capacity of 6500 kw., and a maximum load of 5000 kw., have been extracted from the same report of the Nitrogen Products Committee.

	Cost per Kilowatt Year at 95 per cent load factor.
	£
Salaries and wages	0·438
Oil, stores, and sundries	0·547
Repairs and maintenance	0·803
Capital charges at 10 per cent ..	1·680
Total	3·468

Taking anthracite at 25*s*. per ton, and allowing for a consumption of 0·85 lb. per brake horse-power hour, gives a total annual consumption of 23,500 tons at 95 per cent load factor, corresponding to a fuel charge of £4·7 per kilowatt year, and a total charge of £8·17 per kilowatt year. Based on these figures the approximate over-all pre-war costs at a 35 per cent load factor amount to £4·5 per kilowatt year, and the present-day over-all costs of a new station of this type and size will be correspondingly higher.

8. Limiting Capital Cost of Hydro-electric Plant.—The permissible expenditure on a hydro-electric plant, to compete with a steam-electric plant, depends on the size of the installation, the load factor, and on the cost of fuel. Thus, taking the case of a 20,000-kw. steam plant operating at a 95 per cent load factor, the pre-war cost per kilowatt year of output is £5·92 with coal at 10*s*. per ton, and £7·35 with coal at 15*s*. per ton (fig. 5). Taking 9·5 per cent of the capital cost as giving the cost per kilowatt year of power from the corresponding hydro-electric plant, the permissible capital cost of the latter becomes £62·3 per effective kilowatt if coal is 10*s*. per ton, and £77·2 if coal is 15*s*. per ton. The corresponding limiting costs for other sizes of installation are as follows:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Limiting cost in £ per effective kilowatt with coal at ..	10*s*. per ton	85·5	74·5	62·3	54·5	51·1
	15*s*. ,, ,,	106·0	92·3	77·2	67·6	63·7
	20*s*. ,, ,,	127·5	110·1	92·2	81·0	76·4

These figures are based on pre-war costs of plant, &c., but on a charge of 6 per cent for interest on capital. In the case of a post-war steam plant, using coal at 20*s*. or 30*s*. per ton, and assuming constructional costs at twice pre-war costs, the appropriate figures would be:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in £ per effective kilowatt with coal at	20*s*. per ton	171	149	125	109	102
	30*s*. ,, ,,	212	185	154	135	127

These costs compare with those at the switch-board of the steam-electric station. If the latter is installed near the centre of gravity of the industrial load, and if the hydro-electric station is some distance away, the costs of, and losses due to, transformation and transmission are to be debited to the hydro-electric scheme, and the limiting costs per kilowatt, delivered in bulk at the switch-board of the distributing station, become approximately, on the above basis:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in £ per effective kilowatt with coal at	20s. per ton	148	129	108	94	88
	30s. ,, ,,	183	160	133	117	110

These costs include transformers and transmission lines, and are estimated on the basis that in such a case the cost per kilowatt year amounts to approximately 11 per cent of the total capital costs.

With a load factor of 95 per cent, corresponding to 8320 working hours per annum, the corresponding cost of current in bulk at the switch-board of the distributing station would be:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in pence per B.O.T. unit with coal at ..	20s. per ton	0·470	0·410	0·343	0·298	0·280
	30s. ,,	0·580	0·508	0·422	0·371	0·349

9. Industrial Load Factor.—In the same way, with a load factor of, say, 35 per cent, the limiting capital expenditure per effective kilowatt may be obtained from the appropriate curves of fig. 5. These values are:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in £ per effective kilowatt with coal at	10s. per ton	58·7	50·4	41·9	37·0	34·6
	15s. ,,	70·0	60·5	50·3	44·8	41·9
	20s. ,,	81·4	70·6	58·7	52·6	49·3

In the case of a post-war steam station, the appropriate figures, on the same basis as before, are:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in £ per effective kilowatt with coal at	20s. per ton	117	101	84	74	69
	30s. ,,	140	121	101	90	84

while in the case of a scheme involving transmission over a moderate distance, they become:

Kilowatts.		4000.	10,000.	20,000.	30,000.	40,000.
Cost in £ per effective kilowatt with coal at	20s. per ton	101	87	72·5	64·0	59·5
	30s. ,,	121	104	87·0	77·5	72·5

The corresponding costs per unit of current delivered in bulk at the switchboard of the distributing station are:

Kilowatts.	4000.	10,000.	20,000.	30,000.	40,000.
Cost in pence per B.O.T. unit with coal at .. 20*s.* per ton	0·872	0·750	0·625	0·552	0·514
Cost in pence per B.O.T. unit with coal at .. 30*s.* ,,	1·040	0·900	0·750	0·669	625.0

10. The cost of a hydro-electric station designed to operate at an industrial load factor of approximately 35 per cent is greater than that of one designed to utilize the same water-supply with continuous operation, owing to the greater cost of the necessary machinery, pipe lines, and conduits. The relative cost depends largely on the type of scheme. In a scheme utilizing river flow without storage, the capital cost per effective kilowatt will be sensibly the same whatever the load factor. Where storage is provided to utilize a large proportion of the run-off, the cost of this storage usually forms a large proportion of the total, and as this item of cost does not depend appreciably on the load factor, the cost per effective kilowatt is much less for a low than for a high load factor. In a number of typical installations involving storage, the total cost of an installation designed for an industrial load factor is from 50 per cent to 60 per cent greater than one designed for continuous load, and as in the former case the output in kilowatt years is some 2·7 times as great as in the latter, the cost per kilowatt year is only from 55 per cent to 60 per cent of the cost per kilowatt year of continuous load.

From the figures of the immediately preceding tables it appears that the limiting capital cost per kilowatt at an industrial load factor varies from 65 per cent to 70 per cent of the limiting cost with continuous load, so that an installation of this type, as compared with a steam generating station, will be relatively more economical at a low load factor than at a high load factor. On the other hand a hydro-electric scheme without storage, as compared with a steam generating station, will be relatively more economical at a high than at a low load factor, while for intermediate cases, with partial storage, the relative difference is not likely to be very marked. In any scheme involving a large expenditure on storage, it will, in general, pay to supply as far as possible an industrial, rather than a continuous load.

11. Although the foregoing figures, or similar figures modified to take into account the actual cost of fuel and the actual costs of construction both of the steam and of the hydro-electric installation at the required locality, mark the limiting costs to which expenditure may be taken in competition with a steam-electric station, it would not usually be sound closely to approach these figures in practice. The figures are deduced on the assumption that both steam-electric and hydro-electric stations have a market for their output at full rated capacity. Any failure to attain this full market hits a hydro-electric scheme much more hardly than a fuel-fired scheme, owing to its higher standing charges.

Again, it is a simple matter gradually to build up a steam or gas station, adding successive units to meet an increasing demand, whereas in a hydro-electric scheme it is often necessary to incur a very large initial expenditure in land and in civil and hydraulic works. The fixed charges on this expenditure form a heavy burden during the period of growing demand, and may, if the expected market is not attained, render the cost of generating the power so high as to lead to the ultimate failure of the enterprise. In short, the calculated limiting values should only be approached where a market up to the full capacity of the plant is assured within a few years of its completion.

12. Combined Operation of Hydraulic and Steam Plants.—The combined operation of hydro-electric and steam-electric generating stations is a subject of vital importance to the central station industry, and promises to become increasingly important in the future, since the trend towards interconnection will bring an increasing number of steam plants into parallel operation with hydraulic plants, and will make possible the development of many water powers which cannot economically be developed independently.

The ideal in every combined system should be to obtain a minimum over-all cost of current delivered to consumers. Where the hydraulic and steam stations are separately owned, the solution lies in a flexible arrangement or a co-operative or cost- and profit-sharing basis, in which the maximum output of the hydraulic plant is utilized as far as possible.

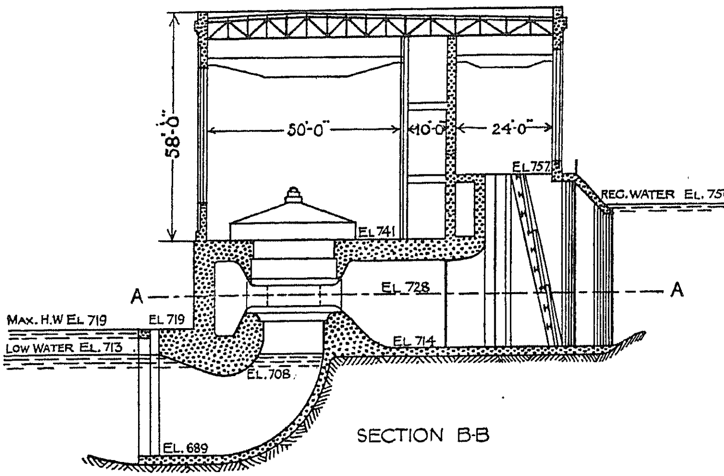
The operating conditions leading to maximum over-all efficiency depend on the special circumstances of each individual plant, and it is necessary to compare the total cost with the steam plant operating at a high load factor —and with the inevitable waste of water which this involves—with the total costs with a low load factor on the steam plant, but with the smaller output which this involves. If the hydraulic plant has a large storage capacity, or a high head, it will usually be found that it is more economical for this plant to deal with the peak loads and to operate at a low load factor. The reverse may, however, be the case if such operation leads to a large loss of water, and if the percentage diminution of steam costs, due to a higher load factor, is relatively small.

13. Stand-by Service.—In coal-burning plants, under-feed stokers with forced draft, or chain grates with forced draft, appear to be most satisfactory for quick steam raising, though future developments will probably tend towards the use of combined coal and oil as a fuel, and of pulverized coal for large central station use. It is worthy of note that in the municipal plant at Zurich it has been found more economical to maintain stand-by boiler pressure by electric heating from the hydro-electric plant, than by coal. This is, of course, only likely to be the case where there is no market for the electricity thus used, and where the water used in its generation would otherwise be wasted.

Tests of the coal consumed under "banking" conditions, for 42 hr., on a 822-h.p. Stirling boiler with underfeed stoker, showed a consumption of

0·112 lb. per rated boiler horse-power hour.* In a similar test on oil-burning boilers, 0·046 lb. of oil, equivalent in heating value to 0·063 lb. of coal, were used.

To avoid the difficulties caused by an accumulation of water in steam-



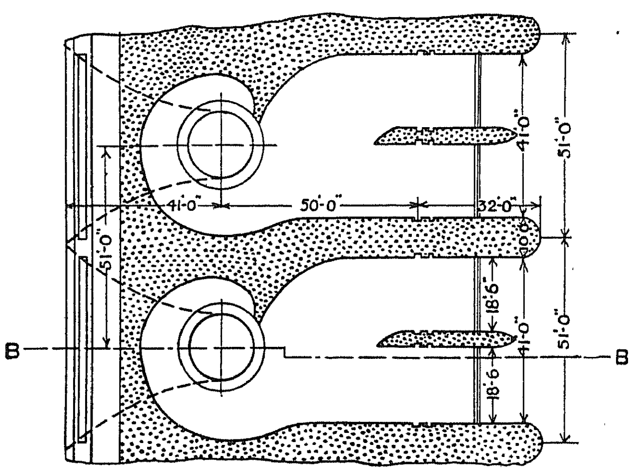


Fig 6

pipe lines during shut-downs, some plants operate at least one boiler at its normal rating during the off-peak hours and use this steam to operate a small unit, circulating the steam through all the mains before it reaches the unit. In other cases the plant is shut down entirely, but steam is blown off for some time near the turbine inlet, before the unit is started up.

* *Report of Committee on Prime Movers*, presented at 43rd Convention of the National Electric Light Association, U.S.A., May, 1920.

The percentage changes in load on the steam plant are greatly increased when the latter plant has to deal with the peak loads, and this condition renders essential some foreknowledge of the load variations, in order to avoid excessive blowing off through safety valves, or reduction of hydraulic output.

Opinion varies widely as to the effect of motoring steam turbines, even with a certain amount of steam entering the turbine. Many engineers consider this, and also any rapid fluctuations of load, as injurious to the turbines. In many cases, however, in American practice, the steam turbines have been floated on the line with practically no load, and in some cases as synchronous condensers with less than no-load steam entering the turbine, without apparent damage.

14. Actual Capital Cost of Hydro-electric Installations.—The cost of development depends essentially upon the physical characteristics of the scheme, and upon whether the output is to be utilized at the site or is to be transmitted to some distance. Since no two schemes are alike in these details it is evident that no even approximate general figure can be given for the cost of development, and that this will vary for each individual installation. In some extremely favourable cases, the capital costs, not including transmission, have been as low as £9 per turbine horse-power installed, enabling power to be generated at approximately £1 per horse-power year. In the great majority of cases the costs are much higher than this. Thus the average cost of pre-war development in Canada and the United States was approximately £25 per horse-power, while the average cost of development in Sweden has been approximately £12 per horse-power. The table on p. 270 shows the figures of costs of a few typical installations.

The following examples are of interest as showing the estimated pre-war costs of development and operation of a number of typical Canadian low-head developments on the Winnipeg River.* In each case single runner vertical shaft turbines are used, and the general lay-out is similar to that illustrated in fig. 6.

Pine Falls Development (figs. 7 and 8).—The scheme involves a masonry dam with spill-way 775 ft. long, with a sluiceway section containing twenty 20-ft. sluices, and with a low embankment 2300 ft. long. The head is 37 ft. Estimates have been prepared for two stages of development, viz. an initial development consisting of six 10,000 h.p. units, and a final development of ten 10,000 h.p. units. The figures give the cost of power, &c., at the low-tension switch-boards of the power station. See p. 272.

* Department of the Interior, Ottawa: *Water Power Resources*, Paper No. 3, Vol. I. These schemes were prepared by Mr. J. T. Johnston, Hydraulic Engineer, Water Power Branch.

Site.	Details.	Cost per Kilowatt Installed.
Kinlochleven, Scotland.	Comprises water storage reservoir with concrete and masonry dam, 3112 ft. long and with a maximum height of 86 ft.; reinforced concrete conduit 3·5 miles long, and six steel pipe lines, 3 ft. 3 in. diameter by $1\frac{1}{4}$ miles long, to power house. Head 935 ft. Power house has Pelton wheel installation with D.C. generators and is adjacent to the aluminium works, where the output is used. Rated output 20,000 kw.	£30·7
Necaxo, Mexico.	Comprises earthen dam 200 ft. high with intake tower, &c.; eight steel pipe lines each varying in diameter from 2 ft. 6 in. to 3 ft. 6 in. Head 1300 ft. Eight turbines and generators with a capacity varying from 8000 kw. to 11,000 kw. each. Total capacity approximately 75,000 kw., transmitted by high-tension system, 93 miles, to city of Mexico, &c. Total cost, including land, equipment, transmission lines, and terminal stations, £3,200,000.	£43 including transmission.
Tasmania.	Water taken from Rivers Ouse and Shannon, flowing from the Great Lake. Available head 1000 ft. Works comprise dam 16 ft. high, conduits, sluices, &c.; two steel pipe lines; power station, with two Pelton wheels and generators; transmission line, 65 miles, to Hobart, with sub-stations and distribution system. Head works constructed for capacity of 40,000 h.p. The pipe lines and power station have a capacity of 9000 h.p. and the transmission line a capacity of 20,000 h.p. Total cost £180,000, made up of headworks, &c., £47,000; power station and machinery complete, £58,000; transmission line, £50,000; sub-stations and distributing system, £25,000. It is estimated that the capacity of the station can be increased to 18,000 h.p. at an additional cost of £72,000. Of this, £12,000 is for an additional transmission line to the existing poles, and £60,000 for an additional pipe line and additional machinery. The cost per kilowatt of the enlarged station would be £18·8.	£26·8 including transmission and distribution.
Chester.	Water from the River Dee, with head varying from 4 ft. to 8·75 ft. Existing weir utilized with some slight modifications, including provision of a fish pass. Works comprise intake sluices, &c.; power station; three turbines, each with its generator and having a total capacity of 635 kw.; and connections to existing electricity mains. Total cost £15,300, made up of buildings, £5200; turbines, £4650; dynamos, £2000; switch-board, £270; fish pass, £500; engineering and other expenses, £2380.	£24·1

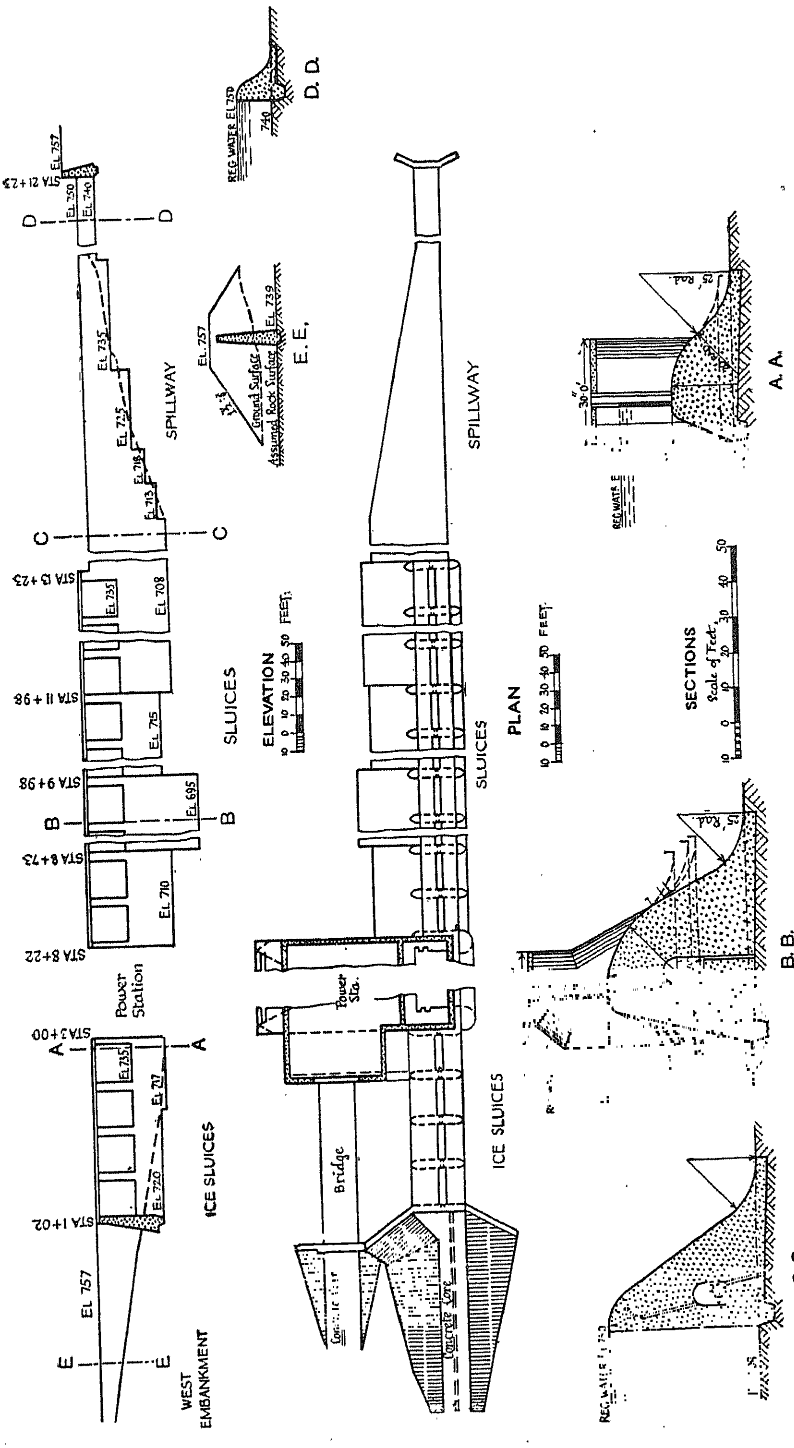


Fig. 8.—Details of Pine Falls Development

1. Initial Development (Six 10,000-h.p. Units)

(1) *Capital Cost of Installation*

	Dollars.	Dollars.
Dam and equipment	381,000	
Ice sluices	61,000	
Power station and equipment	695,000	
Hydraulic installation	540,000	
Electrical installation	720,000	
Dockage facilities	50,000	
Permanent quarters	20,000	
Contingencies, 10 per cent	247,000	
Engineering and inspection, 5 per cent	136,000	
Interest during construction, $5\frac{1}{2}$ per cent	157,000	
Flooding damages	50,000	
Total initial cost		3,057,000

Twenty-four hour power available at 75 per cent over-all efficiency, 37,900 h.p.

Capital cost per 24-hour horse-power	80·66
Capital cost per installed horse-power	50·95

(2) *Annual Cost of Operation*

Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on \$3,057,000		168,000
Sinking fund, 4 per cent (40-year bonds)		32,000
Depreciation—		
1 per cent on permanent works	10,000	
4 per cent on machinery, &c.	56,000	
		66,000
Operation charges—		
Staff	21,000	
Supplies	16,000	
		37,000
Total annual charge		303,000

Annual cost per horse-power year, 24-hour power	\$8·00
Annual cost per horse-power year, machinery installed	\$5·05
Annual cost per kilowatt hour	0·122 cent
Annual cost per kilowatt hour on basis of 50 per cent load factor	0·244 cent

2. Final Development (Ten 10,000-h.p. Units)

(1) *Capital Cost of Installation*

	Dollars.	Dollars.
Dams and equipment ..	381,000	
Ice sluices ..	61,000	
Power station and equipment ..	958,000	
Hydraulic installation ..	900,000	
Electrical installation ..	1,200,000	
Dockage facilities ..	50,000	
Permanent quarters ..	25,000	
Contingencies, 10 per cent ..	358,000	
Engineering and inspection, 5 per cent ..	197,000	
Interest during construction, $5\frac{1}{2}$ per cent ..	227,000	
Flooding damages ..	50,000	
Total final cost ..		4,407,000

Twenty-four-hour power available at 75 per cent over-all efficiency, 63,100 h.p.

Capital cost per 24-hour horse-power ..	69·84
Capital cost per installed horse-power ..	44·07

(2) *Annual Cost of Operation*

Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $4,407,000 ..		242,000
Sinking fund 4 per cent (40-year bonds) ..		46,000
Depreciation—		
1 per cent on permanent works ..	12,000	
4 per cent on machinery, &c. ..	90,000	
		102,000
Operation charges—		
Staff ..	29,000	
Supplies ..	28,000	
		57,000
Total annual charge ..		447,000

Annual cost per horse-power year, 24-hour power ..	$7·08
Annual cost per horse-power year, machinery installed ..	$4·47
Annual cost per kilowatt hour ..	0·108 cent
Annual cost per kilowatt hour on basis of 50 per cent load factor ..	0·216 cent

The following estimates include the cost of transmission to Winnipeg, 64 miles distant, and give the cost of power at the low-tension switch-board in the transformer-house at the delivery end of the line. Transmission is at 66,000 volts. Six 6000-kw. 6600–66,000-volt transformers are provided at the generating station for the initial installation, and corresponding provision, allowing for a 10 per cent line loss, has been provided at the receiving station.

1. Initial Development (Six 10,000-h.p. Units)

(1) *Capital Cost of Installation*

	Dollars.	Dollars.
Capital cost of installation to low-tension switch-board at falls, brought forward		3,057,000
Transformer house at falls	50,000	
Transformers, switches, wiring, &c.	216,000	
Transmission line	360,000	
Transformer house in Winnipeg	45,000	
Transformers, switches, &c.	194,000	
		865,000
Total initial cost		3,922,000
Twenty-four-hour power available in Winnipeg, allowing for 10 per cent loss, 34,110 h.p.		
Capital cost per horse-power		114·98

(2) *Annual Cost of Operation*

Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $3,922,000		216,000
Sinking fund, 4 per cent (40-year bonds)		41,000
Depreciation—		
1 per cent on permanent works	11,000	
4 per cent on machinery, &c.	87,000	
		98,000
Operation charges—		
Staff	36,000	
Supplies	20,000	
		56,000
Total annual charge		411,000
Annual cost per horse-power year, 24-hour power		$12·05
Annual cost per kilowatt hour		0·184 cent
Annual cost per kilowatt hour on basis of 50 per cent load factor		0·368 cent

2. Final Development (Ten 10,000-h.p. Units)

(1) *Capital Cost of Installation*

Capital cost of installation to low-tension switch-board at falls, brought forward		4,407,000
Transformer house at falls	80,000	
Transformers, switches, wiring, &c.	360,000	
Transmission line	420,000	
Transformer house in Winnipeg	70,000	
Transformers, switches, wiring, &c.	324,000	
		1,254,000
Total final cost		5,661,000
Twenty-four-hour power available in Winnipeg, considering 10 per cent loss, 56,790 h.p.		
Capital cost per horse-power		99·68

(2) *Annual Cost of Operation*

	Dollars.	Dollars.
Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on \$5,661,000		311,000
Sinking fund, 4 per cent (40-year bonds)		60,000
Depreciation—		
1 per cent on permanent works	14,000	
4 per cent on machinery, &c.	134,000	
		148,000
Operation charges—		
Staff	45,000	
Supplies	25,000	
		70,000
Total annual charge		589,000
Annual cost per horse-power year, 24-hour power		\$10·37
Annual cost per kilowatt hour		0·159 cent.
Annual cost per kilowatt hour on basis of 50 per cent load factor ..		0·318 cent.

Lower Seven Sisters Fall (fig. 9).—Here the working head is 37 ft. The estimates include provision for a navigation lock 300 ft. × 40 ft., and for 7 miles of construction railway. Estimates are calculated for a complete development of six 10,000-h.p. turbines. The figures represent the cost at the low-tension switch-board of the power station, and do not include transforming and transmission.

1. Complete Development (Six 10,000-h.p. Units)

(1) *Capital Cost of Installation*

	Dollars.	Dollars.
Dam and equipment	668,000	
Ice sluices	86,000	
Power station and equipment	679,000	
Hydraulic installation	540,000	
Electrical installation	720,000	
Permanent quarters	20,000	
Railroad	84,000	
Contingencies, 10 per cent	280,000	
Engineering and inspection, 5 per cent	154,000	
Interest during construction, $5\frac{1}{2}$ per cent	178,000	
Total cost		3,409,000

Twenty-four-hour power available at 75 per cent over-all efficiency, 37,900 h.p.

Capital cost per 24-hour horse-power	\$89·95
Capital cost per installed horse-power	\$56·82

(2) *Annual Cost of Operation*

	Dollars.	Dollars.
Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $3,409,000		187,000
Sinking fund, 4 per cent (40-year bonds)		36,000
Depreciation—		
1 per cent on permanent works	13,000	
4 per cent on machinery, &c.	55,000	
		68,000
Operation charges—		
Staff	21,000	
Supplies	16,000	
		37,000
Total annual charge		328,000
Annual cost per horse-power year, 24-hour power		\$8·65
Annual cost per horse-power year, machinery installed		\$5·47
Annual cost per kilowatt hour		0·132 cent
Annual cost per kilowatthour on basis of 50 per cent load factor ..		0·264 cent

Slave Falls (fig. 10).—Working head 26 ft. Provision is made for a navigation lock 300 ft. × 40 ft., and for 7 miles of railway. Estimates are calculated for an initial development consisting of eight 5000-h.p. units, and for a final development of thirteen 5000-h.p. units. As before, no transmission or transformation charges are included.

1. Initial Development (Eight 5000-h.p. Units)

(1) *Capital cost of Installation*

	Dollars.	Dollars.
Dam and equipment	276,000	
Ice sluices and roadway	35,000	
Head-race	87,000	
Power station and equipment	533,000	
Hydraulic installation	360,000	
Electrical installation	520,000	
Railroad	84,000	
Permanent quarters	15,000	
Contingencies, 10 per cent	191,000	
Engineering and inspection, 5 per cent	105,000	
Interest during construction, $5\frac{1}{2}$ per cent	121,000	
Total initial cost		2,327,000

Twenty-four-hour power available at 75 per cent over-all efficiency, 26,600 h.p.

Capital cost per 24-hour horse-power	\$87·50
Capital cost per installed horse-power	\$58·20

(2) *Annual Cost of Operation*

	Dollars.	Dollars.
Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $2,327,000		128,000
Sinking fund, 4 per cent (40-year bonds)		24,000
Depreciation—		
1 per cent on permanent works	7,000	
4 per cent on machinery, &c.	40,000	
		47,000
Operation charges—		
Staff	19,000	
Supplies	10,000	
		29,000
Total annual charge		228,000

Annual cost per horse-power year, 24-hour power	$8·58
Annual cost per horse-power year, machinery installed	$5·70
Annual cost per kilowatt hour	0·131 cent
Annual cost per kilowatt hour on basis of 50 per cent load factor	0·262 cent

2. Final Development (Thirteen 5000-h.p. Units)

(1) *Capital Cost of Installation*

Dam and equipment	276,000	
Ice sluices and roadway	35,000	
Head-race	204,000	
Power station and equipment	771,000	
Hydraulic installation	585,000	
Electrical installation	845,000	
Railroad	84,000	
Permanent quarters	20,000	
Contingencies, 10 per cent	282,000	
Engineering and inspection, 5 per cent	155,000	
Interest during construction, $5\frac{1}{2}$ per cent	179,000	
Total final cost		3,436,000

Twenty-four-hour power available at 75 per cent over-all efficiency, 44,400 h.p.

Capital cost per 24-hour horse-power	77·39
Capital cost per installed horse-power	52·86

(2) *Annual Cost of Operation*

	Dollars.	Dollars.
Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $3,436,000	..	189,000
Sinking fund, 4 per cent (40-year bonds)	..	36,000
Depreciation—		
1 per cent on permanent works	9,000	
4 per cent on machinery, &c.	61,000	
		70,000
Operation charges—		
Staff	26,000	
Supplies	17,000	
		43,000
Total annual charge	..	338,000
Annual cost per horse-power year, 24-hour power	..	$7·62
Annual cost per horse-power year, machinery installed	..	$5·21
Annual cost per kilowatt hour	..	0·117 cent
Annual cost per kilowatt hour on basis of 50 per cent load factor	..	0·234 cent

Upper Pinawa Site (fig. 11).—18 ft. head. In this case 8 miles of railway are included in the estimate, but no navigation lock. In addition to the dam, about 8000 ft. of low embankment is required. Of this only about 1000 ft. is exposed to a head as great as 5 ft., and 4000 ft. is only required as a protection against occasional flooding. The costs for the complete development of four 4000-h.p. units on the same basis as in the preceding cases are as follows:

COMPLETE DEVELOPMENT (FOUR 4500-H.P. UNITS)

(1) *Capital Cost of Installation*

	Dollars.	Dollars.
Dam and equipment	84,000	
Ice sluices	25,000	
Power station and equipment	385,000	
Hydraulic installation	180,000	
Electrical installation	270,000	
Railroad (8 miles)	96,000	
Permanent quarters	10,000	
Contingencies, 10 per cent	105,000	
Engineering and inspection, 5 per cent	58,000	
Interest during construction, $5\frac{1}{2}$ per cent	67,000	
Total cost	..	1,280,000

Twenty-four-hour power available at 75 per cent over-all efficiency, 12,300 h.p.

Capital cost per 24-hour horse-power	..	104·07
Capital cost per installed horse-power	..	71·11

(2) *Annual Cost of Operation*

	Dollars.	Dollars.
Interest, sinking fund, and depreciation charges—		
Interest, $5\frac{1}{2}$ per cent on $1,280,000	..	70,000
Sinking fund, 4 per cent (40-year bonds)	..	13,000
Depreciation—		
1 per cent on permanent works	4,000	
4 per cent on machinery, &c.	20,000	
		24,000
Operating charges—		
Staff	16,000	
Supplies	5,000	
		21,000
Total annual charge	..	128,000
Annual cost per horse-power year, 24-hour power	..	$10·40
Annual cost per horse-power year, machinery installed ..	..	$7·11
Annual cost per kilowatt hour	..	0·159 cent
Annual cost per kilowatt hour, on basis of 50 per cent load factor		0·318 cent

The following estimates refer to a Canadian development on the Bow River, under a head of 215 ft.* The scheme comprises two dams, one for storage and one for pondage, the main dam being of earthen construction. It also includes a wood-stave flume 7500 feet long, of circular section and 7 ft. diameter; a wood-stave pipe line 1600 ft. long and 7 ft. in diameter; a steel stand pipe; three 1600-h.p. turbines; three 1000-kw. generators; and two exciter units. The estimates are as follows:

	Dollars.
Transportation to site	30,000
Storage dam with spillway, sluices, and controls ..	193,000
Pondage dam with spillway, sluices, and controls ..	145,000
Flume and excavation	110,000
Bridge, &c.	20,000
Surge tank and fittings	22,000
Penstock and valves	23,000
Power house	25,000
Turbines	20,000
Generators	30,000
Switch-gear	12,000
Tailrace	10,000
Engineering and contingencies at 15 per cent ..	96,000
	736,000
Interest during construction, 5 per cent	37,000
	773,000

or $172 per installed turbine horse-power.

* Department of the Interior, Canada, *Water Resources*, Paper No. 2, 1914, p. 105.

The engineer's report on this scheme states: " The scheme is not an attractive one from an economical standpoint. The market for the power must, owing to the high cost per horse-power, be in the immediate vicinity of the plant. It cannot be expected to compete with power in other districts, and it is quite possible that power produced by a steam plant would be cheaper. This can, however, only be settled when the quality of the coal in the locality is known."

The following estimates refer to a British installation developing a maximum of 24,500 h.p. under a head of 170 ft. The scheme includes a concrete dam, a pressure tunnel, an open aqueduct, steel pipe lines, and transmission over 35 miles.

	£
Masonry Dam.	
Excavation between ground-level and 6 ft., 12,000 c. yd.	3,000
Excavation below 6 ft., 30,000 c. yd.	11,000
5 to 1 concrete in dam, 55,000 c. yd.	63,000
Steel work in sluices, 100 tons	2,650
Pressure Tunnel.	
14 ft. diameter, 2000 yd. long	54,000
Conduit.	
18 ft. × 8 ft., 2 miles long	70,000
Penstock chamber and spillway	12,000
Pipe line, 7 pipes, 6 ft. diameter, 190 yd.	11,500
Valves and special pipes	15,000
Power house, 300 ft. × 50 ft.	16,500
Turbines, seven sets of 3500 b.h.p.	16,500
Generators, seven sets of 2650 kw.	31,000
Switch-gear	9,200
	315,350
Contingencies and engineering	47,500
Total cost of hydraulic works and power house	362,850
Transformers (up and down), 18,500 kw.	28,000
Switch-gear	9,300
Transmission line (35 miles)	30,000
Contingencies	10,100
	77,400

15. Cost of Electric Transmission.—Where transmission of electric energy over any appreciable distance is necessary, this adds appreciably to the cost of power to the consumer. The cost of transmission depends not only on the distance, but also largely on the magnitude of the peak load to be transmitted. An excellent example of this is furnished by figures deduced from the annual reports published by the Hydro-electric Power Commission of Ontario, Canada, regarding the Niagara system. This system

supplies some 115 municipalities, and covers a distance 250 miles from the point of generation.

The power is purchased in bulk by the Commission at Niagara Falls, and is sold in bulk to the municipalities, each of which carries out its own distribution, so that the costs incurred by the Commission are those due to transmission only, and are not complicated by the addition of costs of generation and distribution. The Commission operates without profit, and power is sold to the municipalities at the cost price to the Commission plus the proportionate share of the cost of transmission, which includes interest, sinking fund, depreciation, maintenance, loss in transformers and in the line, and all operating costs. The transmission lines have been constructed in accordance with the best practice and with duplicate circuits where advisable. The main lines are of steel-tower construction, but the lower voltage branch lines have wooden towers in many cases. In general the capital expenditure may be taken as moderate.

The cost of transmission for a number of typical cases is shown in the following table.* In all cases the cost of power in bulk at Niagara is $9

THE COST OF ELECTRIC TRANSMISSION

Name of Town.	Distance from Niagara in Miles.	Power delivered.		Cost of Power delivered in bulk. Dollars per Horse-power Year.		Per cent. of total due to Transmission.	Cost of Transmission in £ (£ = $4·86) per Kilowatt Year.
		E.H.P.	KW.	Total Cost.	Portion due to Transmission.		
Niagara Falls	—	2,304	1,720	11·50	2.50	21·7	0·69
St. Catharine's	11	4,520	3,380	14·00	5·00	35·7	1·38
Welland ..	20	4,283	3,200	14·00	5·00	35·7	1·38
Hamilton ..	54	11,622	8,700	14·00	5·00	35·7	1·38
Paris ..	74	357	266	21·00	12·00	57·2	3·30
Guelph ..	76	3,075	2,300	20·00	11·00	55·0	3·03
Toronto ..	90	50,167	37,400	14·50	5·50	38·0	1·53
Kitchener ..	95	4,280	3,200	20·00	11·00	55·0	3·03
Woodstock ..	95	1,331	995	21·00	12·00	57·2	3·30
Princeton ..	96	103	77	66·00	57·00	86·5	15·70
Stratford ..	121	1,519	1,130	27·00	18·00	66·7	4·95
London ..	121	8,552	6,380	21·00	12·00	57·2	3·30
St. Mary's ..	134	397	396	28·00	19·00	68·0	5·23
St. Thomas	134	2,038	1,520	26·00	17·00	65·4	4·70
Ailsa Craig ..	144	80	60	50·00	41·00	82·0	11·32
Granton ..	145	41	31	49·00	40·00	81·5	11·00
Chatham ..	192	889	654	31·00	22·00	71·0	6·07
Dresden ..	208	71	53	43·00	34·00	79·0	9·40
Bothwell ..	214	63	47	59·00	50·00	84·7	13·80
Comber ..	216	20	15	56·00	47·00	84·0	12·90
Walkerville	237	1,972	1,470	38·00	29·00	76·4	8·00
Sanina ..	251	1,126	840	38·00	29·00	76·4	8·00

* H. E. M. Kensit, M.I.E.E., M.A.M.I.E.E., *Electrical Times*, 2nd January, 1919.

per horse-power year, and the total cost is shown in the nearest round figures.

It will be seen that the cost of transmission ranges from 22 per cent to 86 per cent of the total cost of the power delivered. The smaller towns are usually supplied from the general system by short spur lines, and not by separate transmission from the source. While the cost for small amounts of power is high even under these conditions, it would be quite prohibitive in many cases if a separate transmission was required.

From the annual balance-sheet of the commission for the year 1916, it appears that, for the undertaking as a whole, the total costs of transmission amount to 51 per cent of the total cost of the power as sold in bulk. Of the costs of transmission, interest at 3·9 per cent and sinking fund and depreciation at 3·7 per cent account for 69·5 per cent of the total, while wages and salaries at 8·8 per cent, maintenance at 17·4 per cent, and administration at 4·3 per cent make up the remainder.

Similar figures * for a Western Canadian individual installation, in which 14,500 kw. is delivered to the line and transmitted 77 miles at 66,000 volts, show that the transmission costs amount to 47 per cent of the cost of the delivered current. In this case the loss in transformers and transmission was 13 per cent; the load factor was 46 per cent (on the units generated); interest was charged at 4·19 per cent, and sinking fund and depreciation at 4·03 per cent. The fixed charges then amount to 68·5 per cent of the total cost of transmission. The total cost of power at the distributing station in this case is $24·4 per horse-power year. In all these cases the costs are pre-war.

16. Cost of Power to the Consumer.—To obtain the actual cost of hydro-electric power to the consumer, the interest, depreciation, and maintenance on the electric motors and equipment must be added to the price paid for power. The cost of fuel power is usually given per brake horse-power at the engine shaft, and for a fair comparison the cost of electric power must be calculated on the output from the electric motors, with due allowance for the power required to drive any line shafting which they may eliminate.

Taking for example an ordinary factory installation of say 600 b.h.p. of motors, these would cost installed (pre-war) about £3 per horse-power. Assuming power to be sold at 2200 volts, this would usually require transformers to reduce it to 220 or 440 volts, which with housing and equipment would cost approximately £1·2 per horse-power. If the charge for current is based on the metered kilowatt hours measured on the high-tension side of the transformers, a loss of about 17·5 per cent in the transformers and motors would require to be allowed for in making an estimate of the real cost to the consumer. In this case, neglecting the questions of the reduced friction losses in shafting, and of the superiority in steadiness, &c., of the electric drive, the costs to be added to the cost of power at the terminal station would be as follows:

* H. E. M. Kensit, M.I.E.E.

Costs to be added to cost of power at terminal station.

Peak load 500 h.p.; average load 80 per cent.
Diversity factor say 1·2.

Capital cost.

600 b.h.p. of motors installed at £3	£1800
500 h.p. of transformers and equipment at £1·2 ..	600
	£2400

	Load Factor.		
	25 per cent.	50 per cent.	75 per cent.
	£	£	£
Interest and depreciation at 10 per cent ..	240	240	240
Repairs and maintenance	24	48	72
Wages and supplies	20	30	40
Insurance and taxes at 2 per cent	48	48	48
Totals	332	366	400
	£	£	£
Per horse-power year of rated capacity of motors	0·55	0·61	0·67
	Pence.	Pence.	Pence.
Per kilowatt hour of current *paid for*, assuming a loss of 17½ per cent in transformers and motors	·118	·065	·048

It will be seen that with a low load factor this adds very appreciably to the total cost of power to the consumer, and when it is a case of comparing the cost of power obtained from a hydro-electric plant, with power generated directly from a small factory steam plant, these additional costs must be taken into account.

CHAPTER XIII

Tidal Power

Schemes of development; single- and multiple-basin schemes; power available; advantages and disadvantages; general arrangements.

1. The idea of utilizing the rise and fall of the tides for power purposes has long been a favourite one, but up to the present no tidal power scheme of any magnitude has been developed in any part of the world. The lack of data based on operating conditions and on constructional costs renders it difficult to form any definite conclusions as to the economic aspects of such a scheme. Much interest is, however, being shown in this question by Government committees in Great Britain and in France. It is reported that experiments are to be carried out in the latter country, and it is probable that definite data will be available in the near future.

The only practicable methods of developing tidal power on any large scale are based on the use of one or more tidal basins, separated from the sea by dams or barrages, and of hydraulic turbines through which the water flows on its way between the basin and the sea, or between one basin and another.

As will be seen, the power which may be developed from a tidal basin of given area depends on the square of the tidal range, and since the cost per horse-power of the turbines, generating machinery, and sluice-gates increases rapidly as the working head is diminished, the cost per horse-power of a tidal installation, other things being equal, will be smallest where the tidal range is greatest. For this reason the south-western coasts of Great Britain and the western coast of France are particularly well adapted for such developments, since their tidal range is greater than in any other part of the world, with the possible exception of the Bay of Fundy, Hudson's Bay, and Port Gallelos in Patagonia.

2. Tidal Range.—In the great oceans, remote from land, the tidal range varies from approximately 2·0 ft. at spring tides to 0·75 ft. at neap tides. As the tidal wave enters the shallow waters near land its height is increased. For example, round the coast of Great Britain the average range at springs is 16·4 ft., and at neaps 8·6 ft. The configuration of the land affects the range considerably. Where the tidal wave reaches a given point by two routes, as, for example, on the eastern coast of Ireland, where the tide is due to influx from the Atlantic partly around the north, and partly around the south of the island, the resultant tide is compounded of the two, and its range may be either large or very small, depending on

the difference of phase between them. If the high tide of the one coincides with the low tide of the other, the resultant may be practically zero.

The configuration of the coast-line also affects the range considerably. Where the tidal wave enters a long converging estuary, its momentum causes a large increase in its height, and this is responsible for the large tidal ranges at such points as Portishead in the Severn, and St. Malo, where the average ranges at spring tides are approximately 42 ft. and 37 ft. respectively.

The following table shows the approximate values of the mean tidal range at various points.

Locality.		Springs.	Neaps.
Severn	Portishead	42	21·5
	Chepstow	38	19
	Bridgewater Bar	35	18
	St. Malo	37	15·5
	Boulogne	30·5	9·6
	Dee	26	12
	Liverpool	27·5	13
	Le Havre	25	8·0
	Brest	23·5	—
	Beaumaris	23·5	10
	Amlwch	20	11
Thames	Southend	15·5	10·5
	Sheerness	16	10·5
	London Docks	19	—
	Putney	10	—
	Kew	7	—
	Richmond	4	—
	Tay (Dundee)	14·5	8·5
	Montrose	14	8
	Harwich	13	10·5
	Chester	10	—
	Orford Ness	8	6·5
	Lowestoft	6·5	5

The heights of the spring and neap tides vary appreciably during the year. The highest springs normally occur at the beginning of April, and the lowest neaps about the end of February. The highest springs are approximately 15 per cent higher and the lowest neaps 25 per cent lower than the mean springs and neaps. The heights may, moreover, be greatly affected by a strong wind, so that in any tidal installation a possible variation of at least 25 per cent from the mean should be allowed for.

The time of a complete tide is approximately $12\frac{1}{2}$ hr. The rising tide usually occupies a smaller interval of time than the falling tide, the flow usually taking about $5\frac{3}{4}$ hr., and the ebb about $6\frac{3}{4}$ hr. Much, however, depends on the range of the tide and on the physical configuration of the coast, and in a long estuary this inequality of times may be even greater. Thus in the Severn at Chepstow the ebb occupies 7·5 hr. on a spring tide, and 6·5 hr. on a neap tide.

3. The great difficulty in the way of the commercial utilization of a tidal scheme, as compared with an orthodox low-head inland water-power scheme, arises from the relatively great fluctuations in head. In any scheme in which the working head is a definite fraction of the tidal range, the working head at spring tides is much greater than at neap tides. In the case of the Severn, for example, the working head at springs would be twice as great as at neaps, and the energy output per tide would be four times as great at springs as at neaps, while at St. Malo the output would be 5·7 times as great at springs as at neaps.

Not only is the installation subject to this cyclical fluctuation of head, but, in any simple scheme, the turbines cease to operate for a more or less extended period on each tide, and as this idle period depends on the time of high or low tide, it gradually works around the clock, and will, at regular intervals, be included in the normal industrial working day. It is true that schemes of operation are feasible in which this idle period may be eliminated, and continuous operation may be ensured, but only at a considerable reduction of output per square mile of tidal basin area. Even in such schemes, unless the working head is fixed with reference to the tidal range at neap tides, in which case only a small fraction of the total available energy is developed, the variation of head between springs and neaps causes the output to be very variable.

In any installation then, designed for an industrial load, some form of storage system forms an essential feature of the scheme unless the output is cut down to that obtainable under the minimum head available at neap tides, in which case only a very small fraction of the total available energy is utilized, and the cost of the necessary engineering works per horse-power will, except under exceptionally favourable circumstances, be prohibitive.

Various storage systems have been suggested. Electrical accumulators must be ruled out, if only on account of the cost, and the same applies to all systems making use of compressed air. The only feasible system appears to consist of a storage reservoir above the level of the tidal basin. Whenever the output of the primary turbines exceeds the industrial demand, the excess energy is utilized to pump water into the reservoir, and when the demand exceeds the output from the primary turbines, it is supplied by a series of generators driven by a battery of secondary turbines operated by the water from the storage reservoir.

Evidently this method is only available when the physical configuration of the district affords a suitable reservoir site within a reasonable distance of the tidal basin. Unfortunately, also, considerable losses are inevitable in the process. If the

efficiency of primary generators	.. .. ..	= ·95
,, transmission to pump motors	..	= ·95
,, pump motors	.. ..	= ·95
,, centrifugal pumps	.. .. ..	= ·77
,, pipe lines to and from reservoir	..	= ·95
,, secondary turbines	.. .. ..	= 80

the combined efficiency is only 50 per cent, and the energy available for continuous distribution will only be about 60 per cent of the output of the primary turbines, the exact proportion depending on the working period per tide, and on the relative range of spring and neap tides. Where two tidal schemes at some distance apart differ sufficiently in phase, it is possible by working the two in conjunction to reduce or eliminate the idle period between tides, and thus to reduce the necessary storage somewhat, but this does not affect the necessity of storage as between spring and neap tides.

Since storage reduces the available output by about 40 per cent, and at the same time complicates the system, besides adding considerably to the first cost and maintenance charges, the prospects of tidal power schemes would be much more promising if the whole of the output could be utilized as generated. By feeding into a distributing main in conjunction with a large steam station and (or) inland water-power scheme, and delivering to an industrial district capable of absorbing a comparatively large night load, such a state of affairs might be realized, at all events approximately. There is also the possibility that the intermittent operation of certain electro-chemical processes may be developed so as to enable any surplus power to be absorbed as and when available, and, if so, tidal power developed under favourable conditions will probably prove at least as cheap as power obtained from any other source.

4. Schemes of Development.—Many schemes of tidal power development have, from time to time, been suggested. Briefly outlined, the more promising of these are as follows.*

(*a*) A single tidal basin is used, divided from the sea by a dam or barrage in which are placed the turbines. The basin is filled through the sluices during the rising tide. At high tide the sluices are closed. When the tide has fallen through a height whose magnitude depends on the working head to be adopted, the turbine gates are opened, and the turbines operate on a more or less constant head until low tide or slightly after. If A be the surface area of the basin in square feet, if H ft. be the tidal range, if a constant working head of x ft. be adopted, and if the turbines operate until low tide, the volume passing through the turbines during the falling tide will be $A(H-x)$ c. ft., and the energy available in the water will be

$$64Ax(H-x) \text{ ft.-lb. per tide.}$$

This expression is a maximum when $x = H \div 2$, that is, when the working head equals one-half the tidal range, and then equals $16AH^2$ ft.-lb.

If A is in square miles, and if the efficiency of the turbines is 75 per cent, the output in horse-power hours per tide is given by

$$\frac{0{\cdot}75 \times 64 \times (5280)^2AH^2}{4 \times 33{,}000 \times 60} = 169AH^2.$$

* For a resumé of the various systems which have been suggested and patented in the past, reference should be made to a series of nine articles by E. Maynard, *Revue Générale de l'Electricité*, 2nd November, 1918, and following issues, also to a series of articles in the *Engineer*, January, 1921.

The cycle of operations is shown in fig. 1, where AB denotes the working period, and CD the period of replenishment of the basin. Owing to the great variation in the rate of efflux of the water in this constant-head method of operation, the power output varies very largely during the falling tide. This variation may be reduced considerably by arranging the turbines to operate on a more or less constant fall of level in the basin, as shown by the full line AB. By this method of operation the necessary turbine capacity

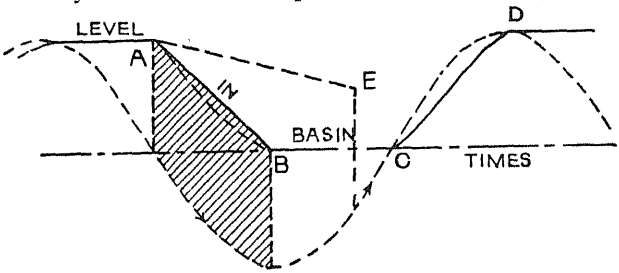


Fig. 1.—Tidal Power Operation with Single Basin, and with Single-way Working

for a given output may be considerably reduced. It has the disadvantage that the working head varies during the tide, but this is more than counterbalanced by the advantages. By extending the working period beyond low tide, as indicated by the dotted line AE, a greater amount of energy may be developed per tide, and the idle period is diminished, but at the expense of an appreciably greater variation in head. The most efficient combination of working period and of working heads can only be determined by detailed

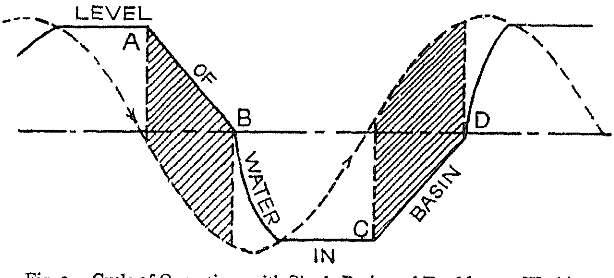


Fig. 2.—Cycle of Operations with Single Basin and Double-way Working

examination of the particular site, and with a knowledge of the exact form of the tidal curve.

(*b*) A single tidal basin is used, with the turbines operating on both rising and falling tides. The cycle of operations is indicated in fig. 2. The working period per complete tide now extends from A to B and from C to D. Slightly before low water, at B, the basin is emptied through sluice-gates, and at D, a little before high water, the basin is filled through the sluice-gates. With a working head equal to one-half of the tidal range, the period of operation is approximately 50 per cent greater than in system (*a*) with operation down to low tide, and the work done per complete tide is approximately 50 per cent greater.

(*c*) A single tidal basin is used with the turbines operating on both rising and falling tides. Instead of filling and emptying the tidal basin through sluice-gates at high and low water, and working under an approximately constant head, the water is allowed to flow through the turbines and to adjust its own level. Under these conditions the rise and fall inside the basin is cyclical, with the same period as the tide, but with a smaller rise and fall and with a certain time lag. The range in the basin and the time lag depend

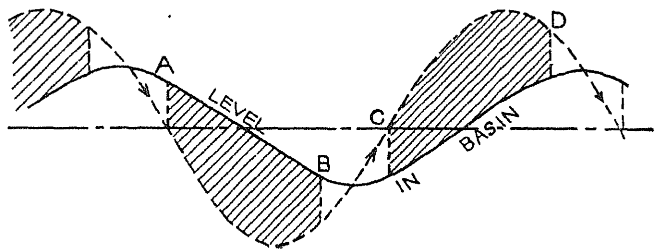


Fig. 3.—Cycle of Operations with Single Basin and Double-way Working

on the ratio of the surface area of the basin and of the effective discharge area of the turbines. The working head during each tide varies from zero to a maximum. The cycle of operations is shown in fig. 3. The working period is from A to B and from C to D, where the head at the points A, B, C, and D is the minimum under which the turbines will operate. The total working period per tide is greater than with either of the preceding systems, and the possible output is somewhat greater. On the other hand, the variation of head during any one tide is large.

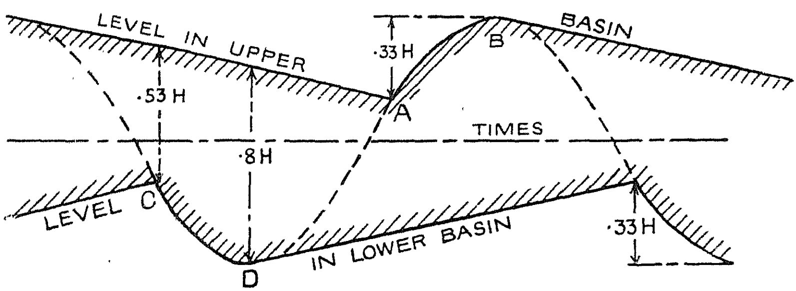


Fig. 4.—Cycle of Operations with Double Basin

(*d*) Two tidal basins of approximately equal areas are used, with turbines in the dividing wall. Each basin communicates with the sea through suitable sluice-gates. In one of these basins, called the upper, the water-level is never allowed to fall below one-third of the tidal range, while in the lower basin the level is not allowed to rise above one-third of the tidal range. The working head then varies from ·53H to ·80H, with a mean of approximately ·66H, and operation is continuous as indicated in fig. 4, which shows the cycle of operations. Between A and B the upper basin is filled from the

sea through appropriate sluice-gates, and the lower basin discharges into the sea from C to D. For a given total basin area and a given tidal range, the output is only about one-half that obtained in system (*a*), and one-third that obtained in systems (*b*) and (*c*), so that except where the physical configuration of the site is particularly favourable, the cost per horse-power is likely to prove high.

(*e*) Two tidal basins of approximately equal areas are used. Turbines are installed in the walls dividing the sea from each basin. Fig. 5 shows the cycle of operations. From A to B the upper basin discharges through its turbines into the sea. From B to E the sea enters the lower basin through its turbines. The upper basin is filled from the sea through its sluice-gates between C and D, and the lower basin is emptied through its sluice-gates from F to G. The head varies from ·25H to ·62H, and the output is some

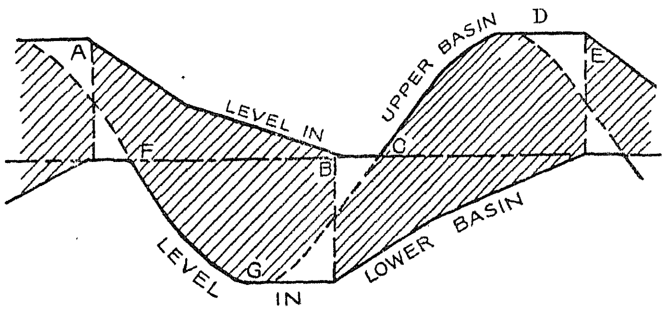


Fig. 5.—Cycle of Operations with Double Basin

25 per cent greater than in system (*d*), but the number of turbines required is greater than in (*d*).

It is possible, at the expense of additional complication, to arrange in each of these systems that the head shall be maintained constant during any one working period, but since this means that the working head is then limited to the minimum obtaining during the period, a loss of energy is involved, with additional cost of construction and complication in manipulation and with little compensating advantage.

For any scheme of development involving the use of a tidal estuary, of such a type as is found in the Severn or Dee, the cost of any of the multiple-basin systems would appear to put them definitely out of court. The only schemes worthy of serious consideration appear to be those based on the use of a single tidal basin, developing power either on the outflowing tide only, or on both rising and falling tides, and with the turbines coupled to generators which deliver directly into the distributing system where the demand permits of this, and which, at other times, supply the motors of a pumping station supplying water to an elevated reservoir, from which a secondary system of turbines is supplied as required, under a constant head. The following investigation is confined to these types of development.

5. The investigation is based on the assumptions that:

(*a*) The area of the tidal basin is 1 sq. mile, and that the water surface

is sensibly level at all stages of the tide, so that the product of the surface area and the change of level at the dam gives the volume leaving or entering the basin per tide.

Actually, in any given case, the area will usually be less at low than at high tide, while in a long estuary the rise and fall immediately above the dam will be appreciably greater than the mean rise and fall in the basin. A contour survey of the basin, along with simultaneous gauge readings at different stages of the tide and at different points in the basin, enable both these factors to be taken into account.

(*b*) The curves for the rising tide and for the falling tide are portions of sine curves. The range at spring tides is 42 ft., and the rising tide occupies

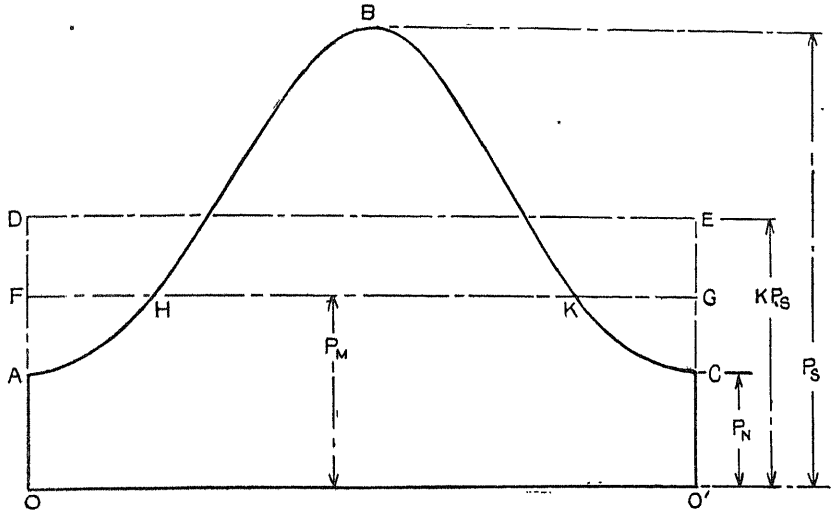


Fig. 6

5 hr. and the falling tide 7·5 hr. The range at neap tides is 16 ft., and both rising and falling tides occupy 6·25 hr.

(*c*) The curve showing the variation of tidal range over a lunar cycle is a sine curve.

(*d*) The output of a given turbine with a given gate opening is proportional to $h^{\frac{3}{2}}$ where h is the working head.

(*e*) The mean efficiency of the primary turbines is 75 per cent.

(*f*) *Mean output during a lunar cycle.*—Where the tidal range for each day during a lunar cycle is known, and the working period and mean head for each day has been settled, the output in horse-power hours per tide, from the primary turbines, may be determined, and a curve may be plotted on a base representing the number of tides, to show the output per tide, as in fig. 6. The mean height of this curve represents the mean output of the primary turbines over the lunar cycle.

Assuming the curve representing the tidal range to be a sine curve with a mean height of H, and a fluctuation of $\pm h$, and assuming the working head

to be proportional to the tidal range, the output per tide with a given turbine capacity will be sensibly proportional to the square of the tidal range, and, for any particular tide, will be equal to

$$k(\mathrm{H} + h \sin \theta)^2, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where k is a constant.

The mean output, over the lunar cycle, will then be equal to

$$\frac{h}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (\mathrm{H} + h \sin \theta)^2 d\theta \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$= k\left\{\mathrm{H}^2 \times \frac{h^2}{2}\right\}\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

If the output in horse-power hours during a spring tide be represented by P_s, and during a neap tide by P_n, we have $\mathrm{P}_s = k(\mathrm{H} + h)^2$, and $\mathrm{P}_n = k(\mathrm{H} - h)^2$, and on substituting in (3) for H and h in terms of P_s and P_n, the mean output of the primary turbines over the whole cycle becomes

$$\frac{3(\mathrm{P}_s + \mathrm{P}_n) + 2\sqrt{\mathrm{P}_s\mathrm{P}_n}}{8} \text{ h.p. hours.}$$

$$= k\mathrm{P}_s \text{ h.p. hours.}$$

If, for example the tidal range at springs is twice as great as at neaps, so that $\mathrm{P}_s = 4\mathrm{P}_n$, the mean output will be $\cdot 594\mathrm{P}_s$, while if $\mathrm{P}_s = 8\mathrm{P}_r$, the mean output will be $\cdot 51\mathrm{P}_s$.

The curve ABC of fig. 6 represents the output per tide in the case where $\mathrm{P}_s = 4\mathrm{P}_n$, while OD represents the mean output per tide over the cycle.

If p per cent of that portion of the output of the primary turbines which is stored and reconverted is lost in the process; if q be the fraction of a complete tide during which the primary turbines operate; and if P_m be the mean output into the distribution system from both primary and secondary turbines, in horse-power hours per tide, the amount of this which may be taken directly from the primary turbines will be equal to q times the mean height of the area OAHKCO′, where OF represents P_m. Calling this mean height X, we have

$$\text{Loss in storage and reconversion} = \frac{p}{100}\left\{k\mathrm{P}_s - q\mathrm{X}\right\}.$$

$$\therefore \text{ Energy into distribution system} = k\mathrm{P}_s - \frac{p}{100}\left\{k\mathrm{P}_s - q\mathrm{X}\right\}$$

$$= \mathrm{P}_m.$$

Very approximately in practice $\mathrm{X} = \mathrm{P}_m$, in which case

$$\mathrm{P}_m = k\mathrm{P}_s\left\{\frac{100 - p}{100 - pq}\right\}.$$

Thus if $p = 50$ per cent, and if the turbines operate for 5 hr. per tide, so that $q = 5 \div 12{\cdot}5 = 0{\cdot}4$,

$$P_m = \left\{\frac{100 - 50}{100 - 20}\right\} kP_s = {\cdot}625kP_s,$$

as compared with the value ${\cdot}50kP_s$ which would hold if all the output of the primary turbines were utilized in pumping into the storage reservoir. If $P_s = 4\ P_n$, so that $k = {\cdot}594$, the value of P_m becomes ${\cdot}371P_s$ or $1{\cdot}48P_n$.

With a system of operation involving a 10-hr. working period per tide, P_m would equal ${\cdot}835kP_s$, a value 66 per cent greater than would be obtained if all the output of the primary turbines were utilized for storage.

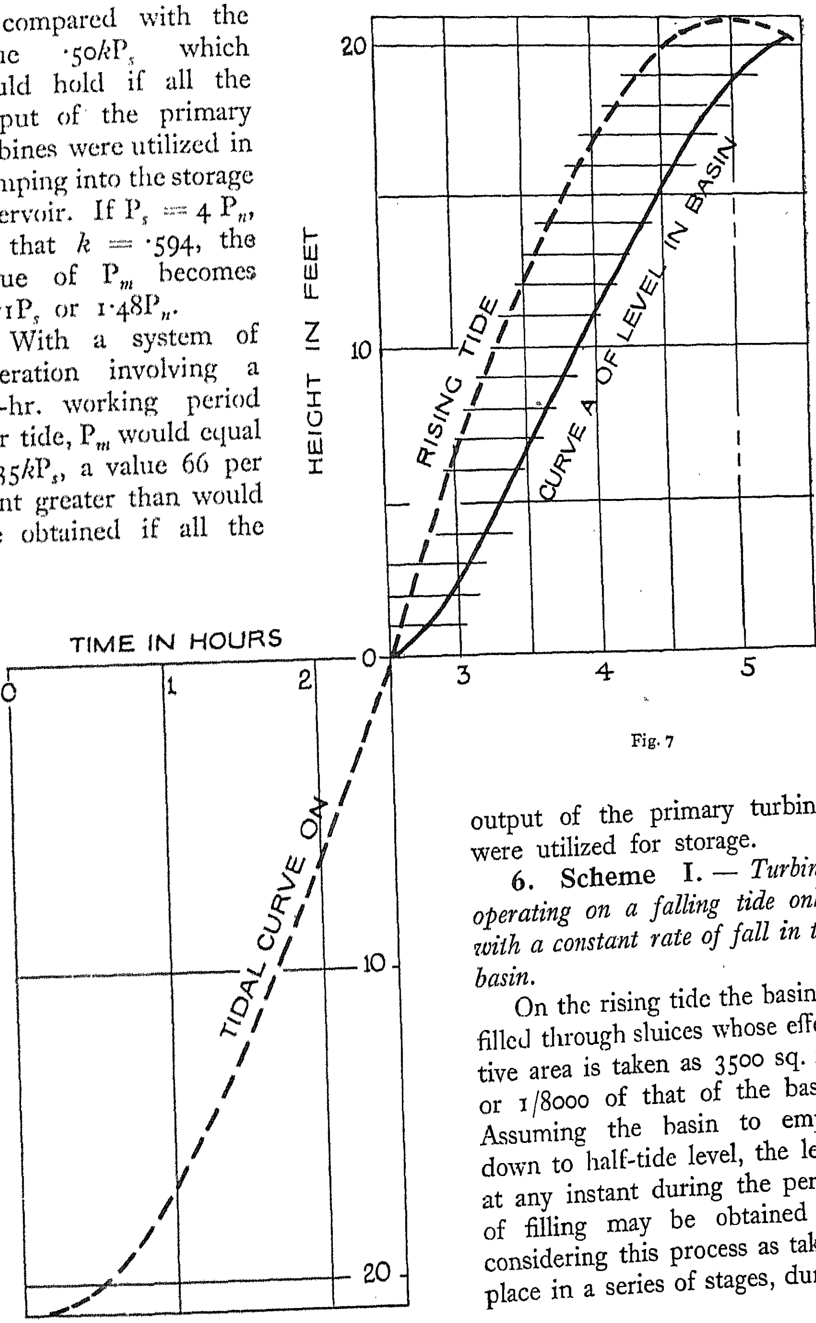


Fig. 7

6. **Scheme I.** — *Turbines operating on a falling tide only, with a constant rate of fall in the basin.*

On the rising tide the basin is filled through sluices whose effective area is taken as 3500 sq. ft., or 1/8000 of that of the basin. Assuming the basin to empty down to half-tide level, the level at any instant during the period of filling may be obtained by considering this process as taking place in a series of stages, during

each of which the head producing inflow may be taken as sensibly equal to the mean during the period. Taking the first half-hour after the commencement of the filling period on a spring tide, for example, if the difference of level at the end of this first stage be assumed to be, say, 4 ft., the mean difference will be 2 ft., and the mean rate of influx

$$\sqrt{2gh} = 11 \cdot 3 \text{ ft. per second.}$$

The rise in level in the basin during this first half-hour will then be

$$\frac{11 \cdot 3 \times 60 \times 30}{8000} = 2 \cdot 55 \text{ ft.}$$

The rise in level outside the basin during this period, as obtained from the tidal curve of fig. 7, is 6·5 ft., so that the difference of level at the end of

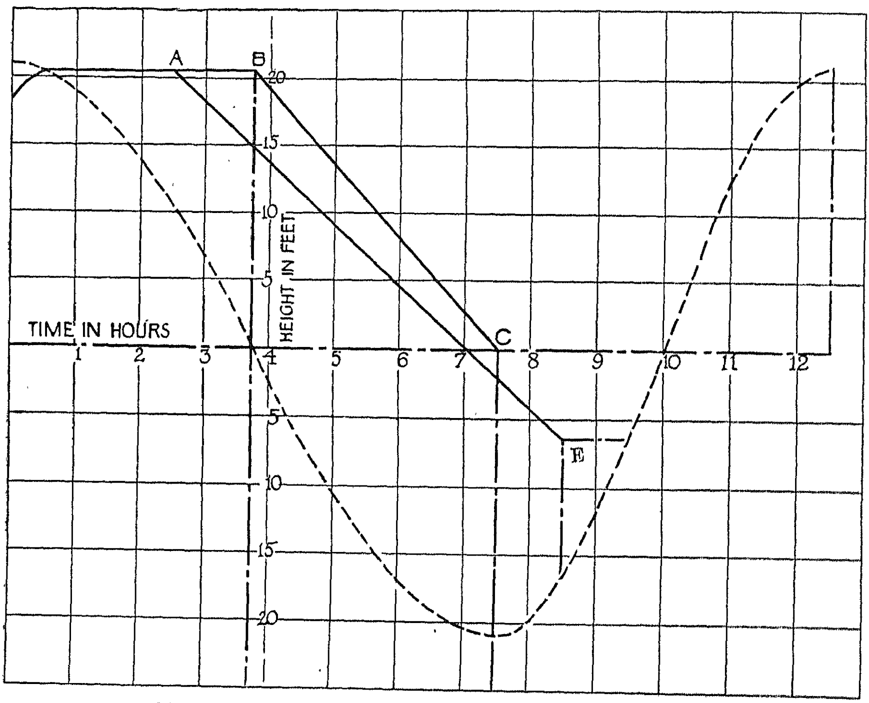


Fig. 8.—Operation on Falling Tide with Constant Rate of Fall in Basin

the period is 3·95 ft., or sensibly as assumed. Proceeding in this way by a process of trial and error, the curve A of fig. 7 is obtained. This shows that the difference of level at high tide is 2·4 ft. If the sluices be left open, the levels inside and outside the basin equalize 25 min. after high tide, the common level then being 0·6 ft. below high tide, or 20·4 ft. above mean-tide level.

If the basin be emptied down to mean-tide level, as in BC (fig. 8), the volume of water passing the turbines per spring tide $= 20 \cdot 4 \times (5280)^2$ c. ft.

If the rate of fall is constant and the initial and final heads each 21 ft., the maximum head, obtained by scaling off the diagram, is 25·0 ft., and the mean head 22·8 ft., so that the output from the turbines

$$\frac{64 \times 20{\cdot}4 \times (5280)^2 \times 22{\cdot}8 \times {\cdot}75}{33{,}000 \times 60} = 315{,}000 \text{ h.p. hours.}$$

The working period occupies 3·7 hours, so that the mean rate of output will be

$$\frac{315{,}000}{3{\cdot}7} = 85{,}000 \text{ h.p.}$$

Similarly, on a neap tide, assuming operation down to half-tide level with an initial and final working head of 8 ft., the mean head becomes 8·76 ft., the maximum head 9·8 ft., and the volume of water passing the turbines $= 7{\cdot}6 \times (5280)^2$ c. ft.

The output from the turbines

$$\frac{64 \times 7{\cdot}6 \times (5280)^2 \times 8{\cdot}76 \times {\cdot}75}{33{,}000 \times 60} = 45{,}000 \text{ h.p. hours.}$$

The working period occupies 3·3 hr., so that the mean rate of output is 13,650 h.p.

The turbines, which at spring tide would develop 85,000 h.p. under a mean head of 22·8 ft., would at neap tides, under a mean head of 8·76 ft., develop

$$85{,}000 \times \left(\frac{8{\cdot}76}{22{\cdot}8}\right)^{\frac{3}{2}} = 20{,}200 \text{ h.p.,}$$

so that only 67 per cent of the turbines would be in operation at neap tides.

Adopting these working heads and periods, and assuming a 50 per cent loss in that portion of the output utilized for pumping in connection with the storage system, the values of k and q (p. 292) become ·525 and ·28 respectively, so that

$$\begin{aligned} P_m &= {\cdot}525 P_s \left\{\frac{100 - 50}{100 - 14}\right\} \\ &= {\cdot}305\ P_s \\ &= {\cdot}305 \times 315{,}000 \text{ h.p. hours per tide} \\ &= 96{,}000 \text{ h.p. hours per tide.} \end{aligned}$$

This is equivalent to a continuous output of

$$\frac{96{,}000}{12{\cdot}5} = 7680 \text{ b.h.p.,}$$

or to an output of three times this, or 23,040 b.h.p. for an 8-hr. working day.

In this scheme of operations the range of working heads is from 25 ft. to 8 ft., and the difficulty of ensuring reasonable efficiencies at constant speed over this range would be great. By reducing the working head at spring

tides, this inequality may be reduced, and by arranging the working period so as to extend beyond low tide, as indicated in fig. 8 (line AE), a greater output may be obtained, while the storage problem is also improved.

Thus, taking a constant rate of fall, and extending the working period over 6 hr. at spring tides, with an initial head of 10 ft., and a final head of 10 ft., the mean head becomes 17·6 ft. and the maximum head 21·0 ft.

The fall in level during the working period is now $20{\cdot}4 + 6{\cdot}5 = 26{\cdot}9$ ft., and the output per spring tide is

$$\frac{64 \times 26{\cdot}9 \times (5280)^2 \times 17{\cdot}6 \times {\cdot}75}{33{,}000 \times 60} = 320{,}000 \text{ h.p. hours.}$$

The mean rate of output is $320{,}000 \div 6 = 53{,}333$ h.p. Evidently the necessary turbine capacity is appreciably less than in the preceding case.

If the operation at neap tides be unaltered, since turbines which are capable of developing 53,333 h.p. under a mean head of 17·6 ft. will develop

$$53{,}333 \times \left(\frac{8{\cdot}76}{17{\cdot}6}\right)^{\frac{3}{2}} = 18{,}650 \text{ h.p.}$$

at neap tides under the mean head of 8·76 ft., 74 per cent of the turbines would be in operation at neap tides.

On the same assumptions as before

$$P_m = {\cdot}520P_s\left\{\frac{100 - 50}{100 - 18{\cdot}8}\right\} = {\cdot}32P_s$$
$$= 102{,}400 \text{ h.p. hours per tide}$$

equivalent to a continuous output of 8200 b.h.p.

Detailed investigation is necessary to determine the most economical development in any particular case. In the case in question, by limiting the turbine capacity to that necessary to absorb the energy available at neap tides, the cost of the turbines, and of the dam in many cases, will be reduced to 74 per cent of its original value. At higher tides some energy would be wasted, the maximum amount being 26 per cent of the energy of the highest spring tide. The output at spring tides would now be 237,000 h.p. hours, and the continuous 24-hr. output, making the usual allowances for loss in storage, would be approximately 7000 b.h.p., or only 15 per cent less than with the original primary installation.

The necessary size and cost of the pumping plant is also reduced appreciably. On the original installation the maximum output of the primary turbines is 69,500 b.h.p., under the maximum head of 21·0 ft., and with a continuous supply of 8200 h.p. into the distribution system; the surplus, to be absorbed by the pumping installation, has a maximum value of 61,300 h.p. With the reduced primary installation the maximum output becomes 51,500 h.p., and with a continuous supply of 7000 b.h.p. into the distribution system the surplus becomes 44,500 h.p. The necessary capacity of the pumping installation is thus reduced by 27 per cent.

7. **Scheme II.**—*Turbines operating on both rising and falling tides, with constant rate of rise and fall in the basin.*

Here it is assumed that the turbines operate on a falling tide to within one hour of low water; that operation commences when the initial head is

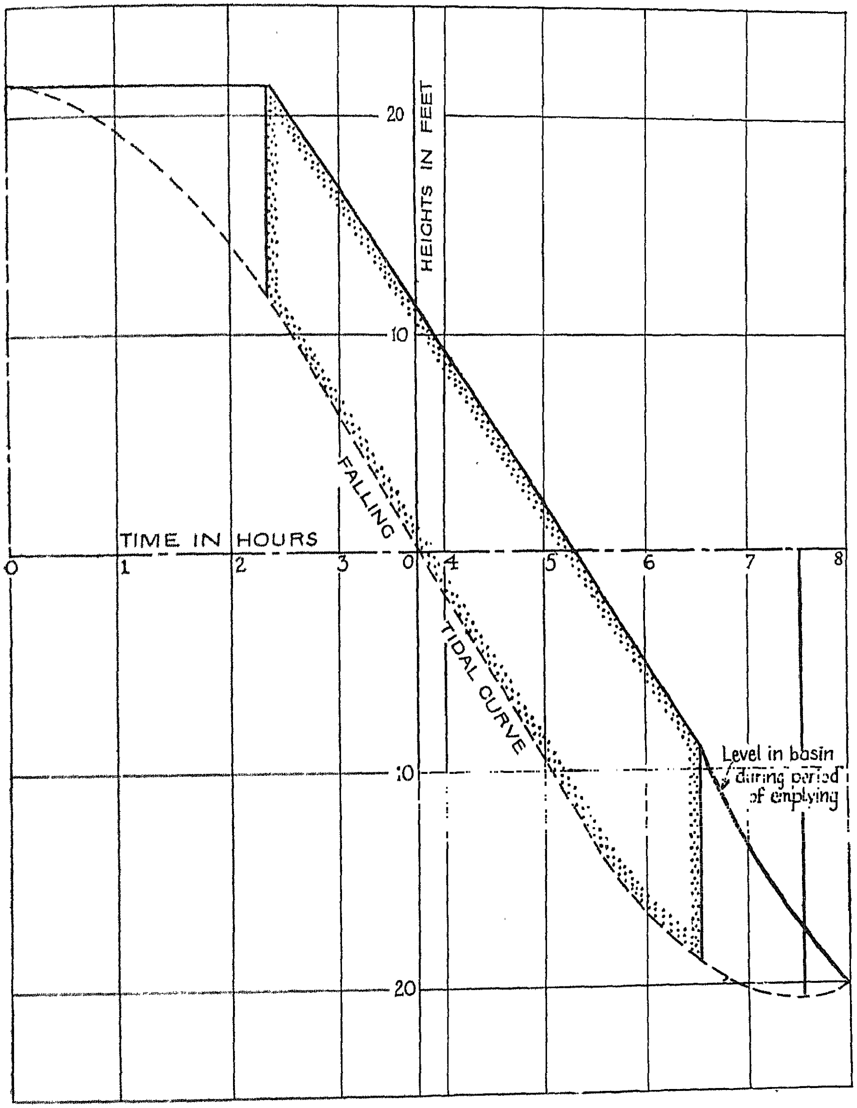


Fig. 9.—Double-way Operation. Falling Tide Period on Spring Tide

10 ft. at spring tides, and 6·5 ft. at neap tides, and that the rate of fall in the basin is maintained constant so as to give the same head at the instant of closing down. One hour before low water the sluice gates are opened, and the basin empties itself during this hour and the succeeding half-hour.

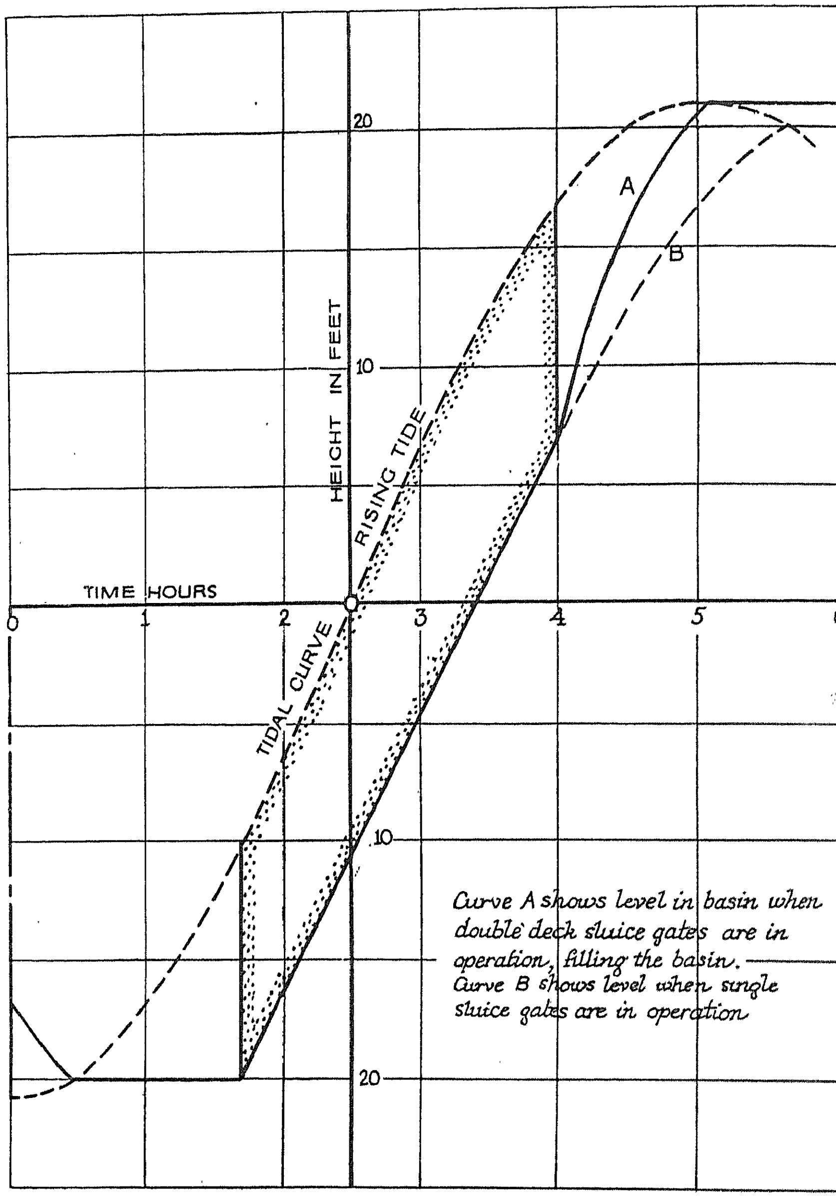


Fig. 10.—Double-way Operation. Rising Tide Period on Spring Tide

On a rising tide the turbines operate under the same heads to within one hour of high water, the basins being filled through the sluices during this hour and the succeeding quarter-hour. At neap tides the turbines are operated to within one half-hour of high and low tides.

The levels in the basin during the periods of emptying and filling have been calculated as indicated on p. 294, and are shown in the curves of figs.

9 and 10. Here it has been assumed that a double bank of sluices is available for use on a rising spring tide, in which case the basins attain the same level ten minutes after high tide, this level being 0·2 ft. below high-water level. Only one set of sluices will be available on the falling tide, and here the levels are identical twenty-five minutes after low tide, the rise of level from low tide at this instant being 0·7 ft.

Spring Tide: Falling Tide ($7\frac{1}{2}$ hr.). — Here the turbines commence operating $2\frac{1}{4}$ hr. after high tide and operate for $4\frac{1}{4}$ hr. The maximum head is 11·9 ft. and the mean head is 11·2 ft. The sea-level at one hour

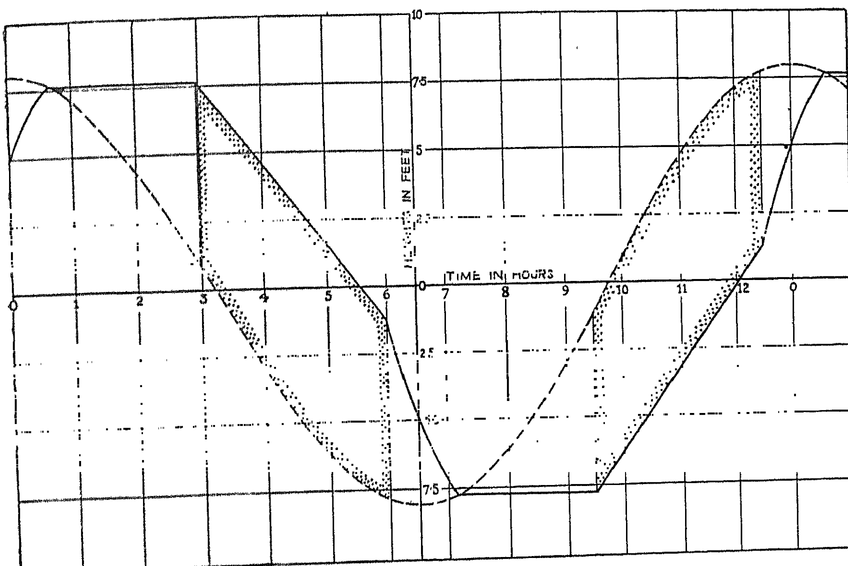


Fig. 11.—Double-way Operation. Neap Tide Curves

before low tide is 2·2 ft. above low-water level, so that during the working period the level falls $42 - 10 - 2{\cdot}2 - {\cdot}2 = 29{\cdot}6$ ft.

$$\text{The output per falling tide} = \frac{64 \times (5280)^2 \times 29{\cdot}6 \times 11{\cdot}2 \times {\cdot}75}{33{,}000 \times 60}$$

$$= 224{,}000 \text{ h.p. hours.}$$

The mean horse-power generated during this period is 52,800 h.p.

Rising Tide (5 hr.).—The turbines commence working $1\frac{3}{4}$ hr. after low tide, and operate for $2\frac{1}{4}$ hr. The maximum head is 11·3 ft., and the mean head 10·8 ft. The sea-level at one hour before high tide is 4·2 ft. below high-water level, so that during the working period the level rises $42 - 10 - 4{\cdot}2 - {\cdot}7 = 27{\cdot}1$ ft.

The output per rising tide = 198,000 h.p. hours.

The mean horse-power during this period = 88,000 h.p.

At Neap Tides (fig. 11) the duration of the operation and the output are the same on both rising and falling tides. The turbines commence

operation 3 hr. after high and low water, and operate for 3 hr. During this period the mean head is 7·15 ft. and the water-level changes by $16 - 6·5 - 0·6 = 8·9$ ft.

The output per falling and rising tide = 43,200 h.p. hours.

The mean horse-power generated = 14,400 h.p.

Making the usual allowance for losses in pumping and storage, the mean output per complete tide over a lunar cycle now becomes 165,000 h.p. hours ($k = ·586$, $q = ·5$), equivalent to a continuous output of 13,150 b.h.p.

Owing to the rapidity with which the tide rises at springs, the turbine capacity necessary to absorb the whole output is 61 per cent greater than that necessary to absorb the whole output on a falling tide, allowance being made for the difference of working heads. In order to reduce the necessary capacity of the primary installation, this may be cut down to that required to deal with the energy available on a falling tide. The output on a rising tide will then be reduced to $198,000 \div 1·61 = 123,000$ h.p. hours, and the continuous 24-hour power available over a lunar cycle becomes 11,000 b.h.p.

Under these conditions, the turbines which at spring tides develop 52,800 h.p. under 11·2 ft. head, would develop $52,800 \times \left(\frac{7·15}{11·2}\right)^{\frac{3}{2}} = 26,900$ h.p. under the mean head of 7·15 ft. available at neap tides, so that 54 per cent of the turbines would be in operation at neap tides.

By adopting a working head of 15 ft. at the beginning and end of operation on a spring tide, and by absorbing only part of the energy of the rising tide as before, the continuous 24-hour power becomes 13,000 b.h.p. The turbines now develop 75,500 h.p. at spring tides, under a mean head of 16·0 ft., and would develop 22,500 h.p. under the mean head available at neap tides, so that the necessary turbine capacity would be 16 per cent less than in the former scheme and 64 per cent of the turbines would be in operation at neap tides. Evidently this is a more efficient scheme than that involving a lower working head at spring tides. The most efficient combination of working heads and working periods can only be determined by detailed examination for each particular case, due consideration being paid to the fact that the higher working heads at spring tides involve a bigger range of working head, and in general a lower over-all turbine efficiency.

8. Scheme III.—*Operation on rising and falling tides, the turbines operating under the natural difference of head existing at any given instant.*

Let a be the effective area of the turbines considered as a series of orifices, so that under a working head x the volume discharged per second is $a\sqrt{2gx}$ c. ft. Let H and h be the heights, above mean sea-level, of the water on the sea and basin sides of the dam, at a time t hours after the instant of mean tide. Then if v be the velocity of efflux at this instant, $v = \sqrt{2g(\mathrm{H} - h)}$ f. s., and the rate of rise and fall of the surface of the basin $\left(\frac{dh}{dt}\right)$ is given by

$$\frac{dh}{dt} = \frac{a}{\mathrm{A}}\sqrt{2g(\mathrm{H} - h)}.$$

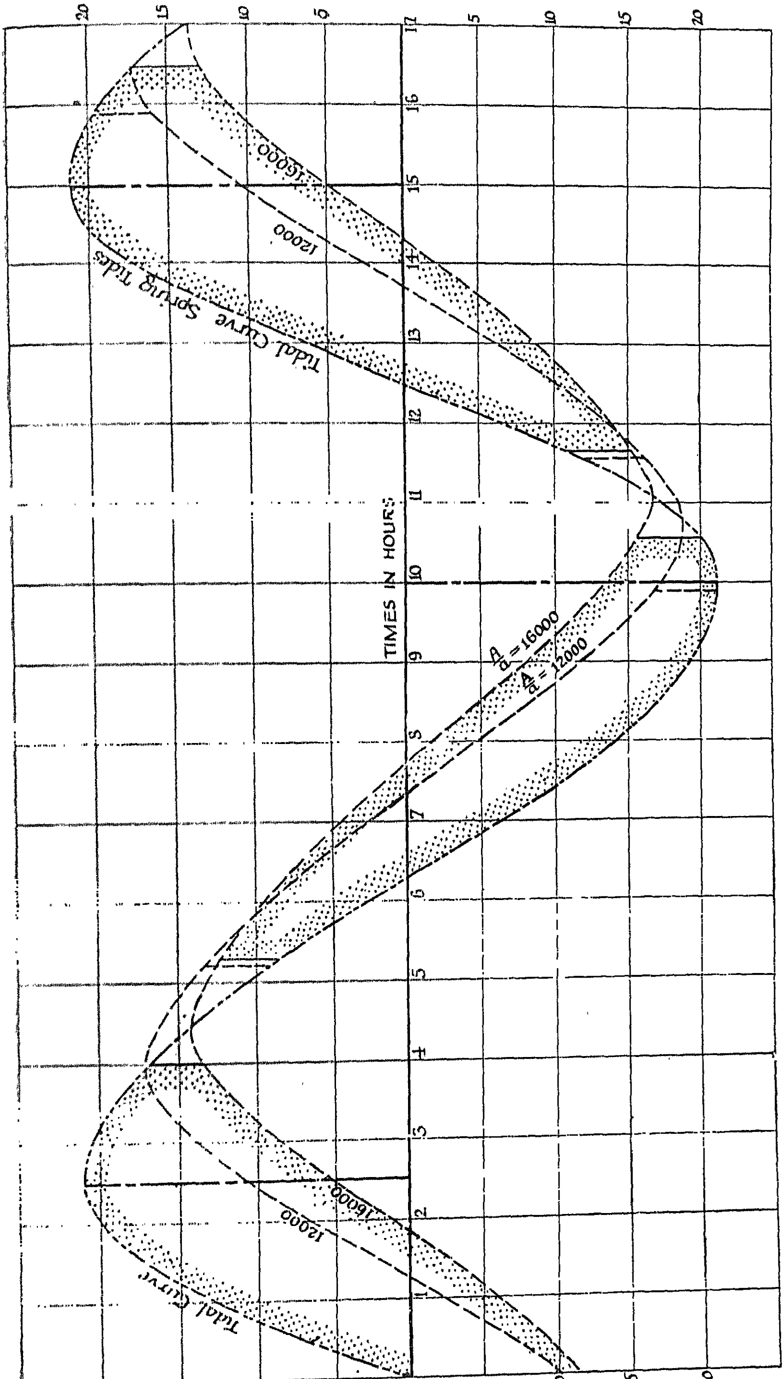


Fig. 12.—Double-way Operation at Spring Tides

Given the form of the tidal curve and the value of A $\div$ a, the solution of this equation gives the value of h, or the level in the basin at any instant. The curve of levels in the basin is a cyclical curve, having the same period as that of the tidal level, but with a smaller amplitude and a different phase. The amplitude and lag depend on the ratio A : a. When this ratio is large, the fluctuation of level in the basin is small, and though the working head is large the power developed is small. When the ratio is small, the fluctuation of level in the basin is large, but the working head is small and the power developed is small. The maximum output is obtained with some definite value of the ratio, which can only be determined by investigation of each particular case.

To construct the curve of basin levels, a value of A $\div$ a and a starting-point on the line of mean tidal height are assumed. Sketching in a probable curve of basin levels, the mean difference of level over a period of, say, 1 hr. from the starting-point is scaled off, and the mean rate of rise in the basin during this period, and therefore the height at the end of the period, is calculated. If this does not agree with the corresponding height on the assumed curve, a second trial is to be made, until the two points coincide. Continuing now from this point, a second period of 1 hr. is taken, and so on until the complete cycle has been covered. If the starting-point has been correctly chosen, the two curves will intersect at similar points on successive cycles. If they do not, another starting-point must be chosen, and the process repeated. A little practice enables the construction to be carried out fairly rapidly. It should be noted, as assisting in the work, that the two curves always cross at a point on the crest of the basin curve, since here the working head is zero, and the rate of rise or fall in the basin is consequently also zero.

An investigation of the case in question shows that maximum output is obtained when A $\div$ a is approximately 16,000 at spring tides, and 30,000 at neap tides. A fairly large variation on either side of the best value does not, however, affect the output greatly, and since an increase in the ratio means a higher working head, and hence smaller turbines for a given output, it is advisable to make the ratio somewhat greater than that corresponding to maximum output.

The basin curves have been drawn for spring tides, for A $\div$ a = 16,000 and 12,000, and for neap tides for A $\div$ a = 16,000, 20,000, 25,000, and 30,000, and are shown in figs. 12 and 13. The output in horse-power hours may readily be obtained from these diagrams, since the volume of water entering or leaving the basin in any period of, say, 1 hr. is given by the difference of level in the basin at the beginning and end of the period, while the head under which this volume is utilized is given by the mean intercept between the tidal curve and the basin curve.

The essential figures for the case in question are as follows:

Spring Tide: Falling Tide (A $\div$ a = 16,000).

Period of operation	= 6·5 hr.
Maximum head	= 12·3 ft.
Mean head on time base	= 8·7 ft.
Output	= 195,000 h.p. hours.

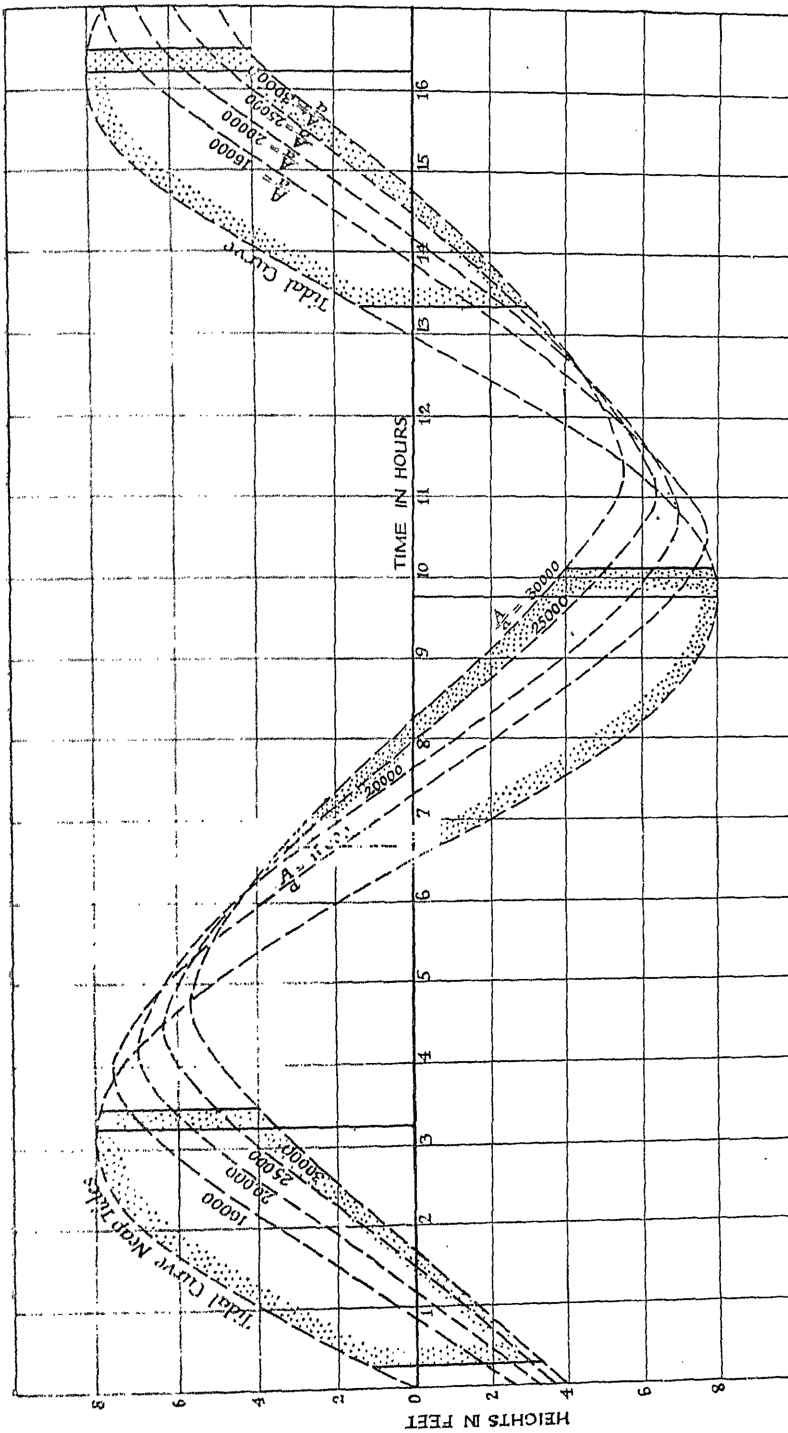


Fig. 13.—Double-way Operation at Neap Tides

If the period during which the head is less than 4 ft. be neglected, these figures become:

Period of operation	= 5·3 hr.
Maximum head	= 12·3 ft.
Mean head	= 9·6 ft.
Output	= 181,000 h.p. hours.

Rising Tide.—Neglecting the period during which the head is less than 4 ft., the period of operation = 4·9 hr.; the maximum head = 19·0 ft.; the mean head = 13·1 ft.; and the output = 252,000 h.p. hours.

Neap Tide, $A \div a = 30{,}000$ (fig. 13).—Since the curves for the rising and falling tides are similar at neap tides, the working period and output are the same for both tides. Neglecting the period during which the head is

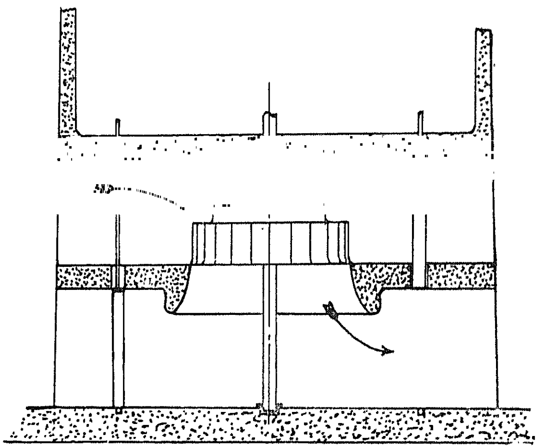


Fig. 14—Setting for Single Bank of Turbines

less than 4 ft., the period of operation becomes 3·4 hours; the maximum head, 6·0 ft.; the mean head, 4·9 ft.; and the output during each of the tides 23,500 h.p. hours.

Combining these results for spring and neap tides gives: $k = {\cdot}47$; $q = {\cdot}68$ (p. 292), and, with the usual allowance for losses in storage, a continuous 24-hour output of 12,400 b.h.p.

For comparison, the essential results of the foregoing investigation are tabulated on p. 305.

9. Advantages and Disadvantages of Different Schemes.—The scheme involving operation on a falling tide only, has the disadvantage that the output is only about two-thirds of the output theoretically possible with double-way operation. On the other hand, the output per unit of turbine capacity is sensibly the same, while it enables a much more efficient type of turbine setting to be used (p. 306), and enables the number of sluice-gates to be halved. It has the further advantage, where applied to a navigable river, that the depth of water in the basin never falls below mean-tide level or thereabouts, so that navigation above the basin is improved. The scheme

Scheme.	Method of Operation.	Continuous 24-hour output, assuming 50 per cent losses in pumping and storage.	Working period for 25 hours.		Working Heads.			
					Springs.		Neaps.	
			Springs.	Neaps.	Max.	Min.	Max.	Min.
I	Falling tide only—with constant rate of fall in basin (a)	7680	7·4	6·6	25·0	21·0	9·8	8·0
	(b)	8400	12·0	6·6	22·5	8·0	9·8	8·0
II	Rising and falling tides—with constant rates of of rise and fall in basin							
	All energy absorbed (a)	13,150	13·0	12·0	11·9	10·0	7·8	6·5
	Only part of energy absorbed on a rising spring tide (b)	11,000	13·0	12·0	11·9	10·0	7·8	6·5
III	Operation on rising and falling tides under natural head	12,400	20·4	13·6	19·0	4·0	6·0	4·0

Scheme.	Capacity (under a head of 13 ft.) of primary turbines required for the scheme.
I (a)	36,700
I (b)	33,600
II (a)	116,000
II (b)	68,000
III	54,000

is essentially more simple than any one involving double-way operation, and the balance of advantages would appear to be heavily in its favour.

Double-way operation under natural head has the disadvantage that the variation in working head is normally very great, while if the conditions be modified so as to reduce this variation, the power developed falls off seriously.

10. General Arrangement of Turbines.—In view of the large number of turbines necessary, and of the great volume of water to be handled, the only feasible arrangement, in a large installation, consists of a long dam, which may require to be curved, or to be carried diagonally across the estuary in order to provide sufficient room for the turbines and sufficient waterway for the necessary sluices. A simple type of setting which has been suggested is shown in fig. 14, and a second type, intended to reduce the necessary length of dam and the number of sluices by installing the turbines in a double

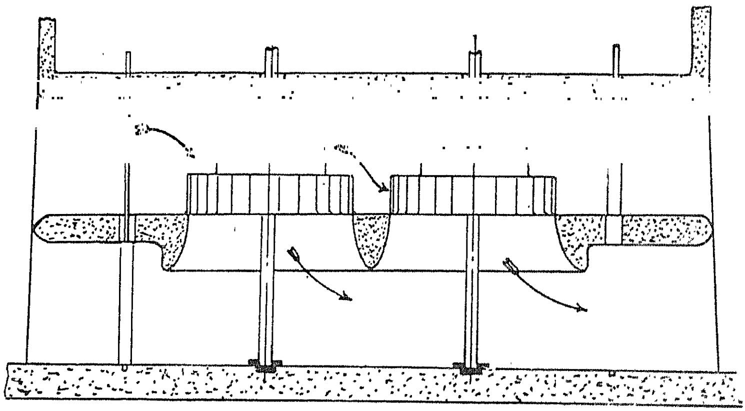


Fig. 15.—Setting for Double Bank of Turbines

bank, is shown in fig. 15. Owing to the fact that the modern low-head high-speed turbine has of necessity a high velocity of flow through its runner, often amounting to as much as $\cdot75\sqrt{2gh}$, it is necessary, for high efficiency, to form the discharge passages with easy curves and gradually increasing sections, so as to reduce the loss of energy at discharge to a minimum, and so as to reduce the velocity of ultimate discharge to something in the neighbourhood of 4 f.s. For example, with a mean working head of 13 ft. (4 m.) the velocity of discharge from the runner, taking this to be only $\cdot5\sqrt{2gh}$, would be equivalent to a head of 2·5 ft., and the maximum possible over-all efficiency of the turbine, assuming a hydraulic efficiency of 85 per cent in the turbine itself, would only be

$$\cdot85\left\{\frac{10 - 2\cdot5}{10}\right\} = \cdot64$$

if the whole of this discharge energy were rejected, as would be the case with either of the settings illustrated. With double-banked turbines, the difficulty of obtaining a sufficient waterway area in the face of the dam, to ensure even

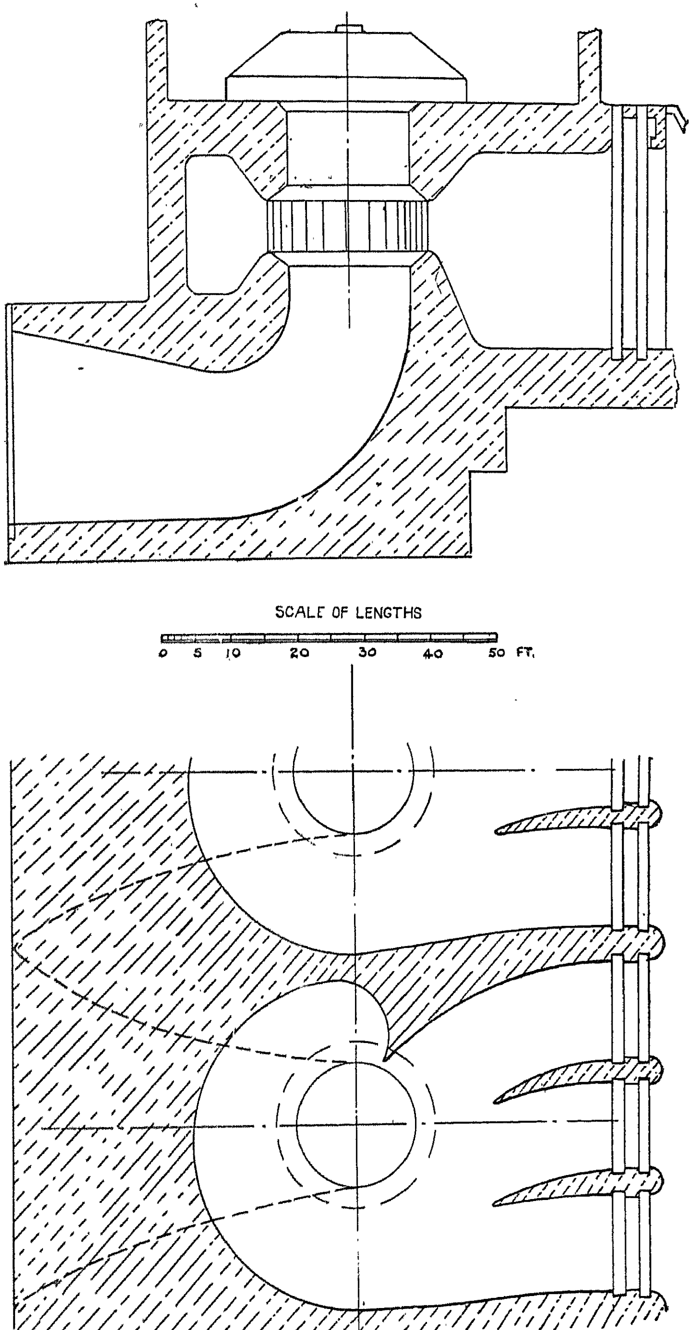


Fig. 16.—Setting for Single Bank of Turbines

such velocities as these, is almost insuperable, and would appear definitely to preclude this type of setting.

The only really efficient type is indicated in fig. 16. Adopting this, a turbine capable of developing 3000 b.h.p. under a head of 13 ft. would require a spacing of about 52 ft., giving an output, under this head, of approximately 60 b.h.p. per foot run of the dam. With smaller turbines the output per foot run of dam would be smaller, amounting to about 50 b.h.p. per foot run for turbines of 2000 b.h.p. capacity.

Thus in scheme I(*b*) (p. 305) seventeen turbines, each of 2000-b.h.p. capacity, would be required, and these would require a dam at least 680 ft. long.

11. Owing to the relatively large variations in working head in any simple scheme, the question of the most suitable type of generating machinery is one of some difficulty.

Under the extreme variations of head occurring in any such scheme, the efficiency of any constant-speed turbine falls off somewhat rapidly, especially at the lower heads, although recent developments of such turbines have shown results which would have appeared impossible only a few years ago. Turbines are now available which are capable of operating under a variation of head equal to 50 per cent on each side of the mean, with efficiencies which do not fall appreciably below 70 per cent over this range, so that this method of operation is quite feasible. It is understood that one well-known firm is prepared to construct variable-speed turbines coupled to constant-speed alternators, and if this can be done without undue mechanical complication and cost, it will probably prove the best solution.

Another possibility consists in coupling the primary turbines to alternators at a fairly low frequency, and to transmit all the power, through a comparatively short transmission line, to motor-driven centrifugal pumps coupled to synchronous motors. In order to avoid the cost and complication of transformers, the limit of voltage might be that for which the machines can be conveniently wound, i.e. about 10,000 volts. Under these conditions the speed of the primary turbines would be allowed to vary with the working head, and the speed of the pumps would vary in the same ratio. In this case multi-stage pumps would be necessary, with provision for adjusting the number of stages in use according to the speed of the primary turbines. This method, involving the storage of all the output of the primary turbines, however, involves a relatively low over-all efficiency.

The difficulties of speed variation and electrical regulation could largely be overcome by the use of direct-current generators, which would enable the turbines to be operated always at the speed corresponding to the available head, and under conditions of high hydraulic efficiency, and in view of the possibilities of the Thury scheme of high-pressure direct-current generation and transmission, this method must be considered as offering a possible solution.

Another possibility consists in coupling the primary turbines directly to centrifugal pumps discharging into the storage reservoir, through one or

more conduits or pipe lines. The practical feasibility of this depends largely on the topographical features of the site. Where the storage reservoir is not in very close proximity to the dam, and where the head is large, the cost of the necessary conduits would in general be excessive. Moreover, the difficulty of arranging the design of the dam so as to include these would be great. It is probable, indeed, that this latter factor would preclude the use of this otherwise simple method in any installation having a long dam and a large number of primary turbines, though it might offer the best solution in a small installation.

For any given scheme it is essential to give full consideration to all the possible mechanical and electrical expedients for developing the power, and to compare these from the view of simplicity, over-all efficiency, first cost, and costs of operation and maintenance.

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